Influencing the precision and efficiency of oral implant treatment by digitalizing the dental workflow

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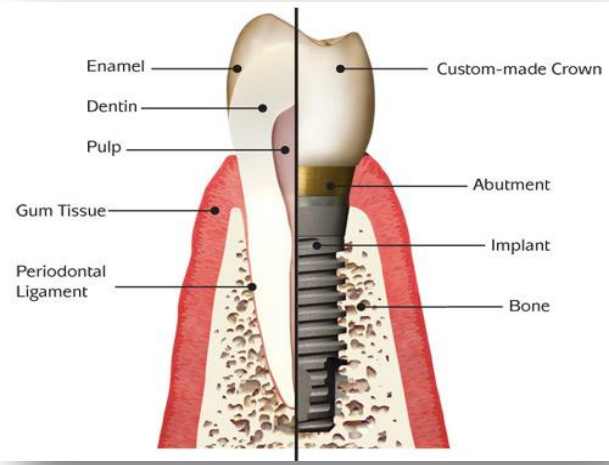
Master Project on

Influencing the Precision and Efficiency of Oral Implant Treatment by Digitalizing the Dental workflow

Precision gestates Profession



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Preface

This report is a master thesis for the study of Business Information System in the faculty of Mathematics and Computer Science Department at the Eindhoven University of Technology (TU/e). This project was conducted within the Information System group at TU/e. It was supervised by dr.ir. H.A. (Hajo) Reijers, who is an Associate Professor in the Information Systems groups and tutored by dr.ir. R.S. (Ronny) Mans who is an post doctor in Information Systems W & I.

The master graduation project started in March 2012 and ended in August 2012. In total, 24 working weeks were spent on the project instead of the usual 21 weeks[1]. The extended three weeks was caused by more effort in redesigning and developing the TO-BE TO-BE dental workflow, extra interviews with dental professionals for the final modelling validation and etc. Before this project, an International Team of Implantology project (ITI project) was derived to investigate the impact of new technologies and processes on the dental value chain. The ITI project is regarded as the benchmark of our project. Thus, the brief overview of the ITI project will be given in the report for your convenience.

It would not have been possible to finish this thesis without the help of others. First of all, I would like to thank Hajo Reijers for supervising my graduation project. Under his guidance, I gained great insight of the methodology to develop an academic research on the process redesign. It is joyful and challenging to work with him.

A special thanks to Ronny Mans, who repeatedly checked the models I developed, explained the result of ITI project and provided me the useful criticism and guidance throughout this project.

I am indebted to a number of dental professionals for assistance with this project. Daniel Wismeyer and Ali Tahmaseb, the dental professionals in ACTA, opened the door of dental world for me and came up with many interesting ideas for the redesigning. Patrick Oosterwijk, dental technician in dental lab, invited me to visit his lab which let me get an clear picture of the dental process. Also thanks to Michiel Van Genuchten, dental workflow expert in dental wing, for his novel ideas and advices on this project.

Last but far from least, I would like to thank my dearly loved girlfriend Zoey and my family who supported me in any respect.

Chenlei Hao
August 2012

[1] 30 ECTS = 30*28 hours = 840 hours = 21weeks of 40 hours

Contents

Chapter 1

1. Introduction

In the first chapter, the background information of this project will be briefly described. After that, the definition of the problem and the structure of this thesis will be indicated.

1.1 Background

For a long time, dentistry has mostly been performed in an analogue world. As Computer aided design (CAD) technique and computer-assisted manufacturing (CAM) is being used in patient treatment and becoming more and more popular, many digitized concepts and technologies have been widely introduced into the dental workflow in an attempt to achieve safety and precision of treatments. This means that in dental processes, many analogue steps have been performed. Especially, when looking at implant planning software, computed tomography and guided implant surgery it is concluded that digital era has already merged into implant dentistry. For the future it is expected that through digital dentistry many improvements can be achieved as many steps can be digitized. Obviously, each switch has the effect that precision is lost. Therefore, in a completely digitized world it is not needed anymore to switch from analogue artefacts to digital and the other way around.

Therefore, the International Team of Implantology project (ITI project) was derived to investigate the impact of new technologies and processes on the dental value chain. The ITI project was concerned with the entire value chain that can be associated with dental implants, covering the stages from patient diagnosis until implant placement. The dentist (General Practitioner or GP), dental surgeon, the dental laboratory and third party digitalization company are the vital parties in this value chain, and the overall quality of this value chain is determined by the actions and interactions between these players. For instance, errors that occur in the translation of implant specifications made at the early stages of the chain will propagate through the entire chain. Meanwhile, improving the efficiency of separate steps can have beneficial effects for the entire chain. Currently, the value chain of interest is characterized by a series of steps that are analogue in nature, which means that they involve the processing or handling of physical artifacts. While an implant itself has a physical manifestation by definition, it can be anticipated that through the application of information technology many other steps will primarily deal with computerized information or half products. This trend can be captured with the phrase of digital dentistry or virtual dentistry.

In the ITI project, a detailed quantitative simulation model has been built of the current value chain, the AS-IS situation, on the basis of information that is obtained with process mining techniques. Furthermore, in order to investigate the effects of digital dentistry on the implant value chain, the simulation model has been used to test hypotheses of three future value chains (TO-BE situation) with respect to reduced time efforts and increased precision due to digitization.

The three future value chains are expected to be valid for the near future (e.g. 3 to 5 years). Hypothesis testing for the value chains revealed a reduced time in order to execute the entire value chain, which is beneficial for patients, and a reduced time in which work is performed by the dental lab. For the dentist, an important player in the entire value chain, no major efficiency gains could be identified. However, during discussions with dental professionals it became clear that for value chains which are valid at a later time in the future (e.g. 5 till 10 years), major efficiency gains for dentists can be expected. This allows for an improvement of the entire dental value chains. Be aware of that, two revised future value chains are developed in this project with respect to increase main gains for dentist.

1.2 Problem Definition

The problem definition and problem context will be given in this section. The problem statement will be presented in the first place, and research goal and sub-research goal will be addressed in the following. The parties that are involved in the project and their boundaries will be discussed afterwards.

1.2.1 Problem statement

In this project, a couple of challenges need to be dealt with . First of all, based on the discussions with dental professionals, it needs to be found out the most promising prospective of the value chains (TO-BE TO-BE model) and efficient key indicators (e.g. reduced time for dentists). Directly associated with these prospective value chains, detailed execution data needs to be identified for it (e.g. asking experts in the field). Finally, by adapting the available quantitative simulation model, the impacts of the prospective value chains are investigated. In conclusion, an answer of what is the TO-BE TO-BE workflow and how impacts can be quantified and evaluated is given in this project.

To better outline the project, 7 sub problems are defined as follows.

- ***Problem 1.*** *What are the current (AS-IS situation) and the three developed (TO-BE situation) dental workflows?*
- ***Problem 2.*** *What methodology and indicators will be used in developing and evaluating the redesigned future dental workflow (TO-BE TO-BE dental workflow)?*
- ***Problem 3.*** *How to develop the redesigned dental workflow that will be valid at a later time in the future (TO-BE TO-BE situation)?*
- ***Problem 4.*** *Comparing to the AS-IS and TO-BE situation, what are the differences of the TO-BE TO-BE situation?*
- ***Problem 5.*** *What are the quantified impacts of redesigned future dental workflows (TO-BE TO-BE)?*
- ***Problem 6.*** *Are there any significant improvements in the aspect of key indicators?*
- ***Problem 7.*** *Is there major efficiency gains for the dentist side?*

1.2.2 Research goal

It is apparent that there are varies challenges to explore a proper value chain in dental workflow. The specified research goal will be defined in the following, meanwhile it will be the aim of this project.

Research goal *Based on integration of new digitalized technologies, designing and simulating the effective dental workflow for the crown treatment and prosthesis treatment that will become valid in the later future (5 to 10 years) and evaluating their quantified improvement.*

1.2.3 Sub research goals

Having formulated the research goal and seven sub problems, seven sub research goals can be derived correspondingly. Based on the following sub research goals, project could be developed in a structured way.

Obviously, the current conventional dental workflow and the redesigned dental workflows are the most important benchmarks for the later future workflow. Therefore, a good understanding of those models is the basis for developing the TO-BE TO-BE workflow. Be aware of that, sub research goal 1 is defined as below.

- ***Sub research goal 1****: Describe and understand the AS-IS, TO-BE situation and the technique improvement in between.*

A structured methodology for developing the TO-BE TO-BE dental workflow should be first defined. After the definition, all works could be done by following the methodology. Furthermore, the devil's quadrangle[1] is used as the evaluation framework in order to evaluate the redesigned dental workflow. There are four different dimensions: cost, time, quality and flexibility. The redesigned future workflows will be evaluated based on each dimension.

- ***Sub research goal 2****: Structure the steps for developing the redesigned future workflows and using the devil's quadrangle to select key indicators for evaluation.*

In order to develop an promising TO-BE TO-BE workflow, the acceptance and approval of dental professionals, such as dentist and dental technician, is very crucial. Thus, sub research goal 3 is described as follows

- ***Sub research goal 3****: Developing the interesting workflows that will become valid in the later future (TO-BE TO-BE situation) and identify it by interviews with dental professionals.*

Through an theoretical analysis, an expect result of key indicators will be given and could be used to validate the result of the simulation. Thus the sub research goal 4 is defined as below.

- ***Sub research goal 4****: Describe the differences of the model and give a theoretical analysis on aspect of key indicators.*

The evaluation of the redesigned future workflow can be done by the simulation by using CPN tool as the dental workflow is modelled in CPN tool. Hence, the sub research goal is stated as follows.

- ***Sub research goal 5****: Quantify impacts of selected future workflows by means of simulation using CPNtools*

Based on the selected key indicators, we will mainly evaluate the differences of "AS-IS vs TO-BE TO-BE" and "TO-BE vs TO-BE TO-BE". The differences between AS-IS and TO-BE will be also briefly described to better explore the improvement from the AS-IS situation to the TO-BE TO-BE situation.

- ***Sub research goal 6****: Evaluate the main difference between the AS-IS, TO-BE and TO-BE TO-BE model.*

At last, it is necessary to see if the redesigned future workflow of benefit for the dentist. The result will be answered with aspect of all key indicators.

- ***Sub research goal 7****: Evaluate the major benefits of the redesigned future workflows for dentist with aspect of all key indicators.*

All the sub research goals are clearly proposed and motivated at different levels in order to achieve the final research goal. The following table shows the matching between every chapter and the each sub goal.

Table 1, project structure

SG	*Phase*	*Description*
SG1	Preliminary	Be acquainted with the conventional dental implantation and the redesigned situation.
SG2	Research methodology	Specify the research methodology including evaluation method, simulation tool and etc.
SG3 SG4	Process model	Brainstorming/discussion/interview with dental professionals and come up with the final TO-BE TO-BE dental workflow.
SG5	Simulation experiments	Implement and simulate the TO-BE TO-BE workflow in CPN tool.
SG6	Evaluation	Use the defined evaluation method to evaluate the TO-BE TO-BE workflow
SG7	Conclusions	Final conclusions

1.2.4 Boundaries

There is no doubt that the whole dental industry is a very broad research area, therefore it is impossible to cover all the processes within this area. Before starting the project, it was clear that two specified dental workflows will be considered here. The decision was made based on the ITI project. As indicated in the background, three redesigned dental workflow are already developed in the ITI project, thus designing an later future dental workflow is becoming available. As an extension of the ITI project, this project will be based on the models and the available resources of ITI project. Therefore, only two dental workflows that are addressed and redesigned in ITI project will be taken into account in this project. To clear the scope of the project, these two dental workflows could be specified by two factors which are patients and treatment methods.

Patients. Obviously, patients are the most important factor in describing a dental workflow. Based on the figure below, patients can be divided into 3 types, which are completely edentulous patients, partially edentulous patients and other patients. In this project, only two type of patients will be considered in terms of the two dental workflows, one is partially edentulous patients and the other one is completely edentulous patients.

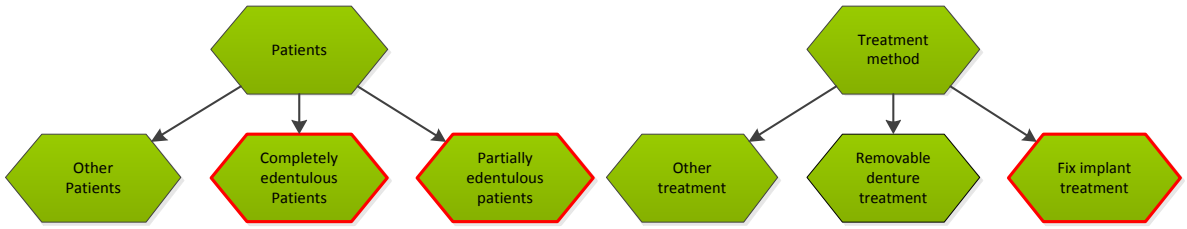


Figure 1, boundaries of patients and treatment method

Treatment methods. From the figure above, there are 3 kinds of treatment under treatment method. In this project, we only consider the fixed implant treatment. Fixed implant treatment means that the replacement of crown or prosthesis cannot be removed from the mouth, not even by the dentist, without breaking it. The patients who are willing and able to receive the fix implant treatment rather than removable denture treatment will be considered in this project.

Furthermore, reasonable technologies have to be involved to ensure that the dental workflow can be proper redesigned. From this purpose, only developed and developing technologies (e.g. surgery guided technique and intra oral scan) will be selected. Remainder of the report will be addressed within this boundary.

1.3 Document Structure

Based on the planning, the rest of the report is structured as follows.

- Chapter 2 **Preliminaries**. The basic idea of dental workflow will be explained in the first place. Meanwhile, a description of crown and prosthesis treatment will be described in this chapter.
- Chapter 3 **Research Methodology**. The research methodology will be clearly explained.
- Chapter 4 **Process Models**. Describe the operating process of the current situation (AS-IS model), near future situation (TO-BE model) and far future situation (TO-BE TO-BE model). In general, the main process and key players will be discussed.
- Chapter 5 **Simulation Experiment**. Based on the gathered data, all experiments' results will be listed in this section.
- Chapter 6 **Evaluation**. The evaluation method will be described. Furthermore, comparisons among there different models will be indicated based on the experiments' results.
- Chapter 7 **Conclusion**. The results will be analyzed and the final conclusion will be given.

Chapter 2

2. Preliminaries

The general background information and process of conventional dental implantation for each type of patients will be presented in section 2.1 and 2.2, where all the evidence is coming from interviews with dental professionals and literature review. Furthermore, the conventional model and redesigned model of crown and prosthesis treatment in AS-IS and TO-BE situation will be described subsequently.

2.1 Introduction of conventional crown placement

Conventional crown replacement could be defined as a procedure that replaces damaged or missing teeth with artificial teeth that look and function much like real ones. In general, the dental implantation could be described as a five-phase procedure that includes intake phase, surgery phase, healing phase, abutment placement phase and final crown placement phase. The five steps will be conducted sequentially. as showed in the figure below.

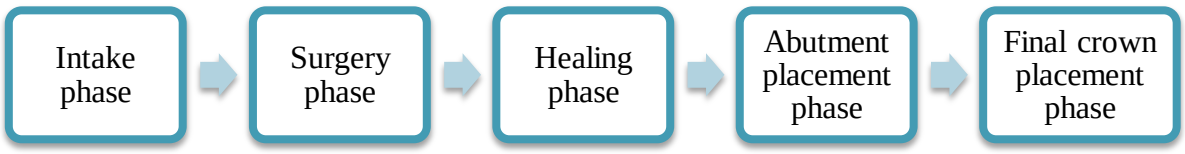


Figure 2, five phases of conventional dental implantation

2.1.1 Intake phase

In this phase, depending on the needs and situation of the patient, dentist will give a certain advices and perhaps the expected result of the treatment. Meantime a thorough examination will be adopted to check the healthy level of patient, since if the patient is pregnant or has cancer, undergoing the surgery may lead to serious problems.

2.1.2 Surgery phase

After the intake and certain number of medical checking, the surgery of placing implants could be started. The idea of the surgery is shown as follows. First create an gum flap[2] that is big enough. Then raise the gum flap up to expose the bone underneath which have to be sufficient for the visible and accessible of the dentist. In the end, use the drilling tools to drill an implant hole at the planed position and screw the implant into the bone. The patient's needs and the reviewing X–rays will be taken into consideration to confirm size and placement of the implant.[3]

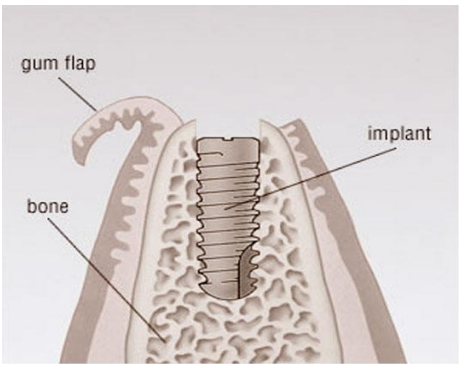


Figure 3, raise the gum flap

2.1.3 Healing phase

During the healing phase, both the osseointegration and wound healing will be happened. Especially, it is important to get acquainted with the osseointegration of dental implants since it is the key determinant of this treatment. The following definition of osseointegration is given by Benjamin Miller and Claire Keane:

Definition of Osseointegration. The formation of a direct interface between an implant and bone, without intervening soft tissue.[4]

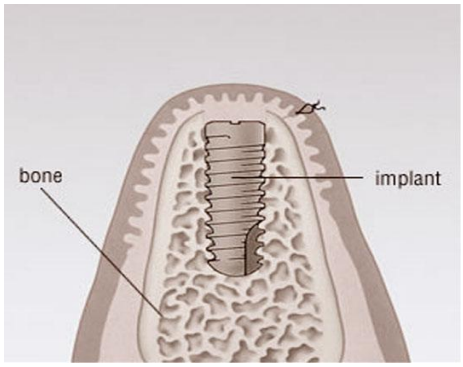


Figure 4, Oseeointegration

The main reason that the implant surgery can be successfully is that the implant and the bone can be integrated without interposition of soft tissue. In other words, osseointegration can be described as a phenomenon where implant integrates with living bone, firmly anchoring the implant in place. Nowadays, installation of dental implants is the obvious uses for the osseointegration.

Healing phase is one of the key phase contributing to the total throughput time of the treatment. In general, it require two to six months for the osseointegration (osseointegrated into the bone) and wound healing before entering the next phase.

2.1.4 Abutment placement phase

Once the implant is installed and the bone has started growing into it, it will be impossible to remove without damaging the bone, and it will be capable of bearing weight after the healing phase. At this point, fitting abutment could begin.

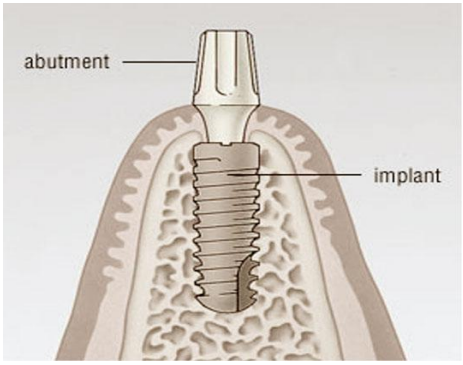


Figure 5, placement of abutment

Dental Implant Abutments are connecting pieces that join the prosthesis to the implants.[5]

First of all, the implant needs to be surgically exposed by removing some of the overlying gum. At second stage, the surgeon checks the implant for its successful integration and connects abutment through the gum into the mouth. Abutments come in many forms and can be stock-manufactured or custom-molded by the dentist and the dental technician.[3] When placing the final abutment, dentist will keep it in line with the rest of the teeth in order to achieve an aesthetic result. Once the abutments are placed, dentist will need to make a copy of it by way of taking a dental impression. Most dentists will take an impression of your tooth using a paste or putty-like compound that's often referred to as simply "impression material." The idea is that the completed impression is sent to a dental laboratory where it's used to create a plaster cast that, in turn, is used when they fabricate your crown. Since the cast is a precise representation of your tooth and its neighbouring teeth, if the crown is made to fit precisely on it, it should fit accurately on your tooth too. (Normally, a little bit of adjustment is still necessary.)[6]

2.1.5 Crown placement phase

Placement of Dental crown is usually a two appointment procedure with several weeks gap in between. Taking impression are always done in the first dental appointment. The function of temporary dental crown is to prevent sensitivity to hot and cold food stuffs to prepared the tooth. It also has the function of aesthetics if it is placed on the front tooth. Impression is sent to the dental laboratory

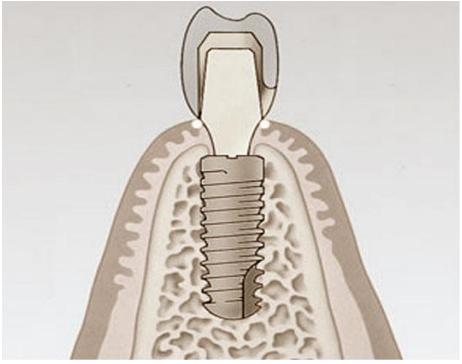


Figure 6, placement of final crown

technician for fabrication of permanent dental crown. It takes several weeks to complete dental crown fabrication in lab. The temporary dental crown will be removed and the permanent dental crown will be placed during the second dental appointment. Moreover, the evaluation of the fit and appearance of permanent dental crown is done before the cementation. The dentist will make sure that the permanent dental crown is placed properly, and he/she will cement the completed dental crown in place. It is worth to mention that the placement of dental crown can be done within single dental appointment if in the dentist's office there is a ceramic milling machine.[7]

Use of Ceramic Milling Machine (CAD-CAM Technique)

"*After tooth reduction, an optical impression of the tooth is taken which is displayed on computer screen. Dentist designs the crown using computer aided designing (CAD) and it is then transferred to ceramic milling machine and this machine prepares the crown from a ceramic block using computer aided machining (CAM). So, there is no need of any lab procedure and crown is fabricated and cemented in a single appointment. But crowns prepared by this technique are much expensive.*"[7]

2.2 Introduction of conventional prosthesis placement

Conventional prosthesis replacement is applied to the completely edentulous patients. This treatment is very different from crown replacement even though they share the same ideas in intake phase, surgery phase and healing phase. In this case, a permanent bridge will be attached directly to the implants rather than the abutments. Besides, there are more implants will be inserted into the jawbone to fix the prosthesis, but the exactly number of implants is determined by the specific requirements of each case. In the end, the custom bridge or steg with the fabricated prosthesis will be fitted into the patient's mouth and screwed directly into the implants. Basically, conventional prosthesis replacement also can be considered as a five phases procedures but with some differences in the last two phases. The last two phases are prosthesis fitting phase and final prosthesis placement phase instead in this case.

The prosthesis fitting phase is usually a two appointment procedure. In the first appointment, the patient will be required to take impression, and the impression will deliver to the dental lab for the temporary prosthesis making. During the second appointment, the dentist will check the fitness of the temporary prosthesis for the patient.Unfitted temporary prosthesis will be returned back to the dental lab for the further adjustment by dental technician, and the fitted temporary prosthesis will be the model for producing the final prosthesis.

The permanent prosthesis will be placed in the final phase. First of all, the fitness and appearance of the permanent prosthesis will be evaluated. The dentist will screw the finished prosthesis in the place only when the prosthesis is seating in an appropriate way.

2.3 The process model of crown placement (AS-IS situation)

The AS-IS model will be briefly described in this section. Conventional crown replacement workflow is modeled by Petri-net in the ITI project. In order to obtain an overview of the model, only compulsory task will be mentioned and briefly explained and the descriptions of optional tasks can be find in ITI project.

In the AS-IS model, two process lines, front line and back line, are added for the purpose of easier understanding. In the front line, the tasks should be finished with the involvement of patients, thus one or several appointments are necessary for the front line tasks. In the back line, the tasks should be finished with the involvement of dental lab, thus the products transportation between the front line and back line will be taken into consideration.

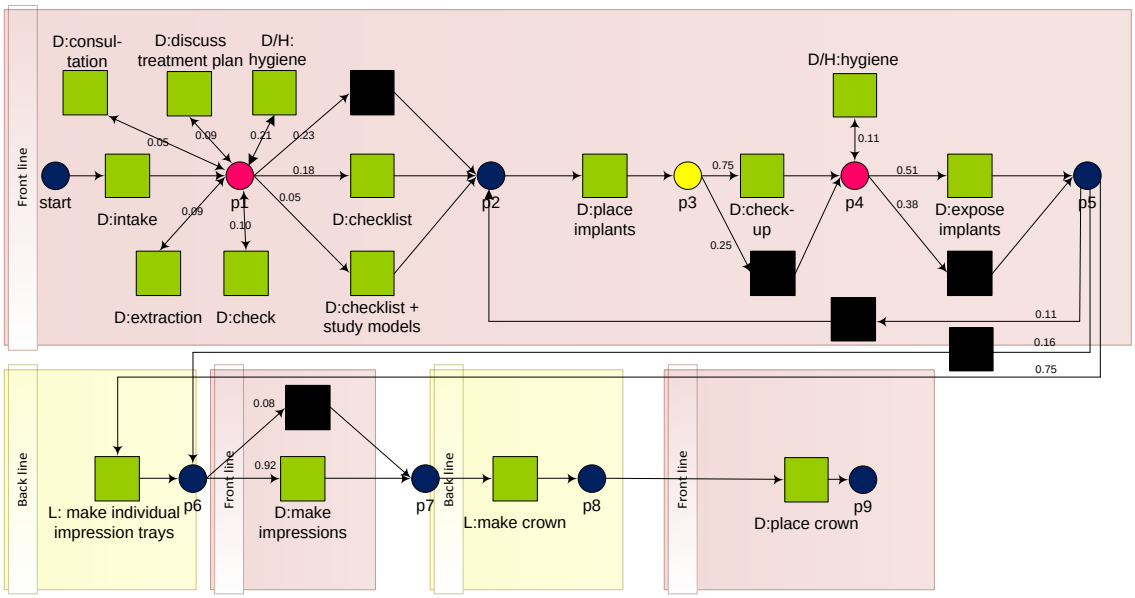


Figure 7, AS-IS model of crown treatment

The AS-IS model is displayed in the picture above. The main procedures of the model are briefly described as below:

1. "**D: intake and preparation for treatment**". Patient has the first dental appointment with dentist for consultation, discussion of treatment and etc. Thorough medical checking might be executed if it is necessary. For some patients, the extraction of the broken teeth will be happened in preparation step.
2. "**D: place implant**". Based on the pre-defined planning, surgery for placing implants is completed in this part
3. "**D: expose implant**". After the healing phase and osseintegration, the implants are exposed by dentist for taking impression.
4. "**L: make individual impression trays**". Patients will first receive a pre-impression which is initially taken with a prefabricated tray. This provides the technician with a rough overview of patient's jaw for producing the individual impression tray. Thus, first the pre-impression will be transported to the dental lab and based on that technician make individual impression trays.
5. "**D: make impressions**". Individual impression could be made immediately once the produced individual impression tray arrives at dentist's office.
6. "**L: make individual plaster model**". The finished individual impression is delivered to the dental lab. Based on the impression, dental technician could start to produce the plaster model.
7. "**L: make crown**". According to the plaster model, dental technician could select permanent abutment and make the temporary tooth. The selected abutment and temporary tooth will be transported to the dentist's office where the fitness of the abutment and shape of crown could be tested. If the pre-produced crown is fitted, then dental technician could start to produce the permanent crown with the same colour and shape of the tested one.
8. "**D: place crown**". All the finished crowns are carefully transported to dentist side for the final replacement.

Based on explanations above, we could conclude that:

- There are at least five appointments between patient and dentist.
- There are at least four times transportation between the dental lab and dentist side.
- No digital workflow between dental lab and dentist.

- Except the medical devices such as implants, all the products or by-products are manufactured manually. Note that implants are not individually produced for a patient, it is just selected from stock.

2.4 The redesigned model of crown placement (TO-BE situation)

Based on the AS-IS situation, a TO-BE workflow is designed by adopting the Intra Oral Scan (IOS) in ITI project. The Petri-net model (see figure below) is explained as below.

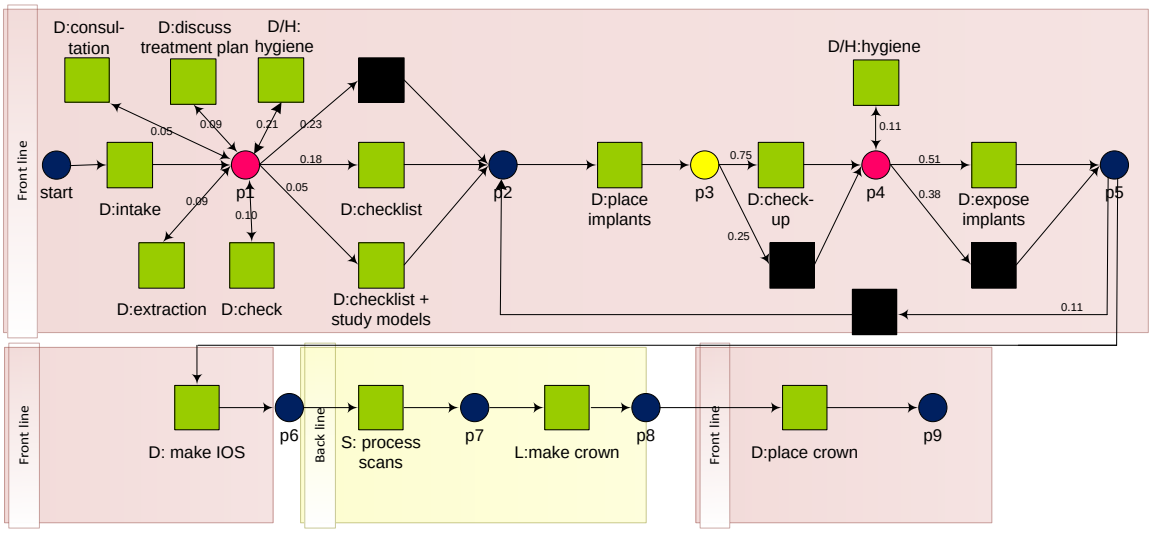


Figure 8, TO-BE model of crown treatment

Main modifications:

- "***D: make IOS***". After exposing the implants, intraoral scanning is adopted instead of the traditional impression making aiming at dealing with problems and disadvantages of traditional impression fabrication process.
- "**L: process scan**". Without the physical transportation of impressions, the digital impression from IOS will be digitally delivered to the dental lab.

Solved problem:

Experience has shown that 50% of the conventional impressions, that arrive from dental practices at dental laboratories, do not fulfil the requirements due to the human errors or limitation of materials of impression, and that only 10% of them are repeated.[8] To reduce human errors and improve the quality of impression, the IOS is introduced. In terms of the limitation of materials, IOS are driven by several non-contact optical technologies and principles, thus it is a material-free technology. The result of IOS is completely digital impression that could reduce the human errors as well. Furthermore, it could also prevent the damage of the impression occurred during the transportation.

Benefits:

- ***Time reduction***. IOS is much faster than traditional impression making, since the impression retakes is eliminated, restoration remakes is reduced, and may help to avoid time-consuming adjustments in the later steps. In addition, the time for delivering impressions is eliminated.
- ***Patient satisfaction***. IOS is an attractive alternative to conventional impression taking, since the unpleasant taste of the impression material and gag sensations are uncomfortable for some patients. The material free technology reduces the preparation works for patient.

- ***Flexibility***. The digital impression gives the flexibility for dentist to choose and work with different dental laboratories. Also, the IOS is suitable for all dental restorations, tooth- and implant-based, including inlays, onlays, veneers, crowns, partial crowns and bridges.
- ***Cost saving***. Even through the machine of IOS is relatively expensive, all cost for materials, transportations and impression producing can be saved.
- ***Improved workflow***. The two appointments are reduced to one stop of IOS, and transportation between dentist and dental lab is partially also reduced.

Drawbacks:

- There are at least five appointments between patient and dentist.
- There are at least one times transportation between the dental lab and dentist side.
- There is a long healing time after placing implants.
- Dentist has to wait for the response from dental lab for the final treatment.

2.5 The process model of prosthesis replacement (AS-IS situation)

The general information regarding the workflow of conventional prosthesis replacement is given in this section.

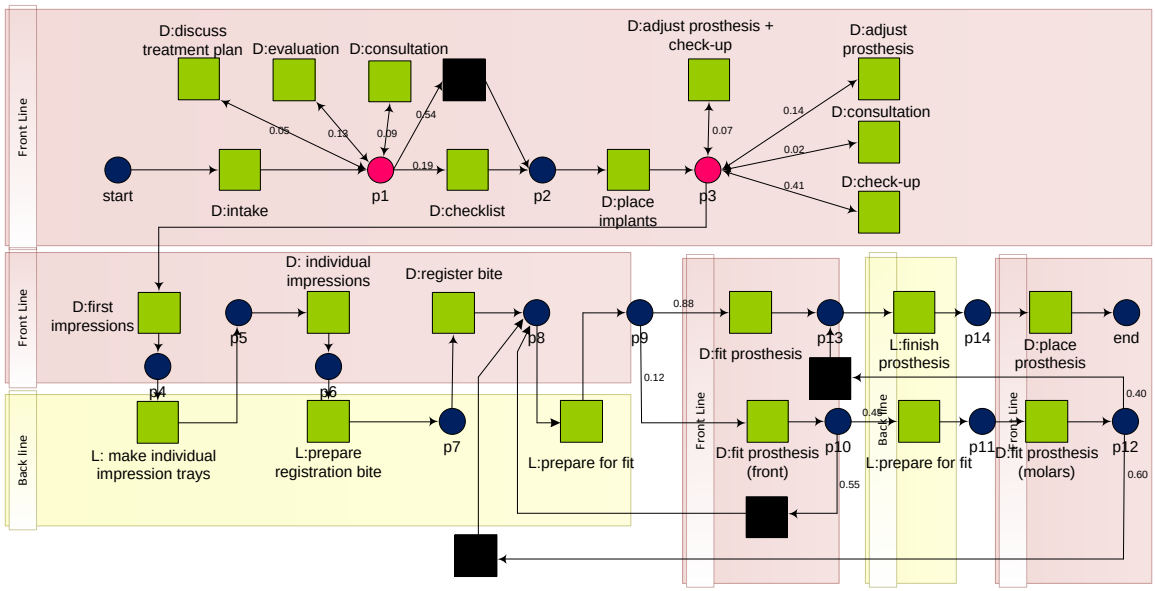


Figure 9, AS-IS model of prosthesis treatment

As showed in the model, the main procedures could be briefly described as below:

1. "**D: intake and preparation for treatment**". Patient has the first appointment with dentist for consultation , discussion of treatment and etc. Thorough medical checking will be done if it is necessary.
2. "**D: place implant**". Dentist will give a surgery to the patient and place all the implants in patient's mouth according to the discussed planning. After that, there will be 3 to 6 months healing time.
3. "**D: First impression**". After the wound was healed, dentist will make a first impression for the patient.
4. "**L: make individual impression trays**". Based on the impression made by dentist, the dental lab will design a specific impression tray for the patient.

5. "**D: make individual impressions**". Milling the impression tray on the toothless jaw, dentist could make a unique and accurate individual impression for the patient.
6. "**L: prepare registration bite**". After obtained the individual impression, dental technician in dental lab will start to make tool for registering bite.
7. "**L: register bite**". Dentist register the bite for the patient and sent it to dental lab.
8. "**L: prepare for fit**". Once registered bite is arrived at the dental lab, dental technician could design a wax prosthesis depends on the individual impression and registered bite, and send it to the dentist.
9. "**D: fit prosthesis**". Dentist adjusts the wax prosthesis in patient's mouth to check its fitness.
10. "**L: finish prosthesis**". If the wax prosthesis is fitted, then dental technician could duplicate the fitted prosthesis to produce the permanent prosthesis.
11. "**D: place prosthesis**". The produced permanent prosthesis are carefully transported to dentist side for the final replacement. Dentist installs the final prosthesis into the mouth of the patient.

Based on the discussion above, we can conclude that:

- There are at least seven appointments between patient and dentist.
- There are at least seven times transportations between the dental lab and dentist side.
- There is no digital workflow between dental lab and dentist.

2.6 The redesigned model of prosthesis placement (TO-BE situation 1)

Compared with the crown placement model, there are two TO-BE models developed for prosthesis placement in the ITI project. One is designed by adopting the Intra Oral Scan (IOS) from the AS-IS model. The Petri-net model is explained as below.

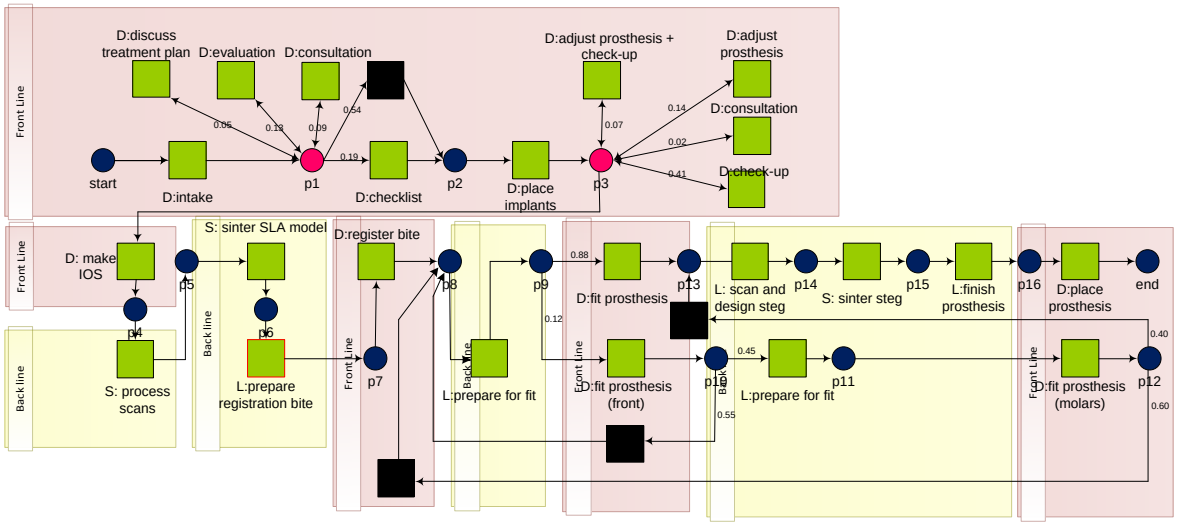


Figure 10, TO-BE 1 model of prosthesis treatment

Main modifications:

- "***D: make IOS***". After placing the implants, intraoral scanning is adopted instead of the traditional impression making in order to deal with problems and disadvantages of traditional impression fabrication process.
- "**L: process scan**". The digital impression will be digitally delivered to the dental lab from IOS rather than physical transportation. The dental technician can make the plastic model based on the processed scan then.

The solved problems and benefits of IOS in redesigned model of prosthesis treatment are same as those in redesigned crown treatment model.

Drawbacks:

- There are at least six appointments between patient and dentist.
- There are at least five times transportation between the dental lab and dentist side.
- There is a long healing time after placing implants.

2.7 The redesigned model of prosthesis replacement (TO-BE situation 2)

The other developed TO-BE workflow is designed by adopting three mini implants in ITI project. The Petri-net model is showed as below.

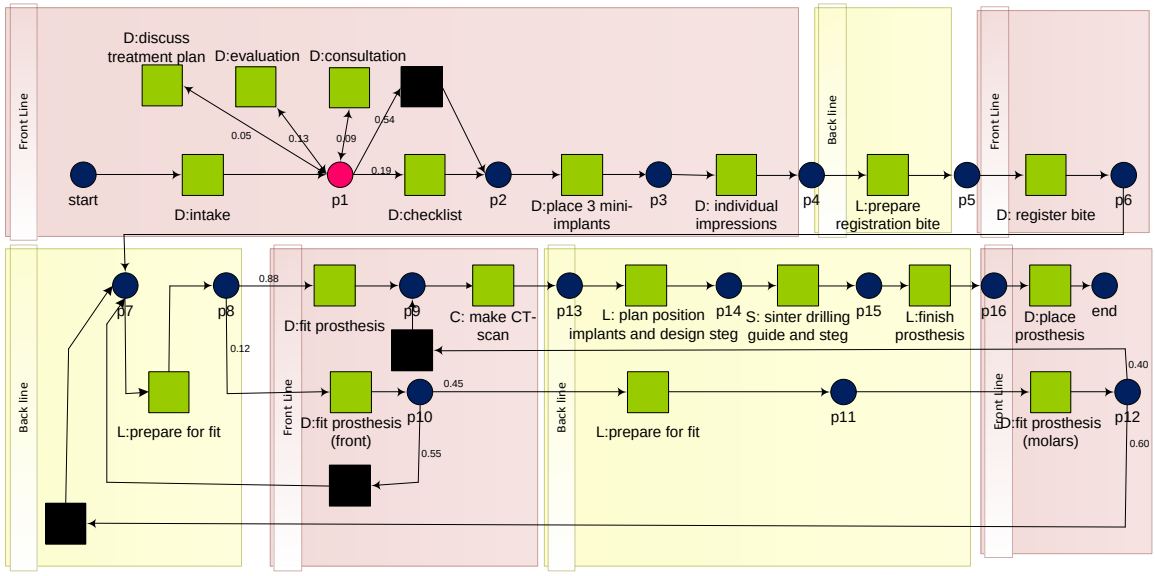


Figure 11, simplified TO-BE 2 model of prosthesis treatment

Main modifications:

- "***D: place three mini implants***. Instead of placing all the implants, dentist only place 3 mini-implants into the jawbone. This surgery is quite different from the one that place all the implants. In this case, it is not necessary to raise the entire gum flap for placing mini implants.
- "***D: individual impressions***". After placing mini implants, dentist is able to make a first impression for the patient immediately (there is no healing time between the placement of 3 mini-implants and making the first impression).
- "***D: make CTscan***". After fitting the wax prosthesis, dentist will make a CT-scan for the patient with the prosthesis is on (the crown on the temporary prosthesis is made by barium material which is visible in the CT scan).
- "***L: plan position implants***". Based on the fitted wax prosthesis and CT scan, dental technician are able to virtually plan positions of implants and design bridge or steg as all the mini-implants and fitted prosthesis are visible in the CT-scan.
- "***L: sinter drilling guide***". With the virtual planning, a drilling guide is produced in the dental lab. With the help of drilling guide, dentist could place the implants accurately.
- "***D: place prosthesis***". This is very different from placing prosthesis in the AS-IS situation. In this case, dentists not only need to place the permanent prosthesis but also have to place the normal implants. Since the permanent prosthesis is already well designed and produced, a

drilling guide is necessary to guarantee the accurate placing of implants. After implant placement, the three mini-implants and drilling guide will be removed from patient's mouth. In the end, the final prosthesis could be placed directly on top of the implants.

Solved problems:

Osseointegration and healing will take approximately three to six months which contributes a major part for the total throughput time of prosthesis treatment. To reduce the total throughput time, the mini-implant technology is adopted as healing phase is eliminated for placing mini-implants. Attaching to the mini-implants, the temporary prosthesis can be firstly produced and placed before placing normal implants. Afterwards, dental technician are able to produce the duplicate of the fitted temporary prosthesis and drilling guide, which allows dentist to place all the normal implants and final prosthesis within one appointment with patient. In this redesigned workflow, the whole procedures will be addressed before the osseointegration, and there is no big gum flap so that the healing time is also eliminated.

Benefits:

- ***Time reduction***. Significantly reduce the total throughput time of the treatment. Note that the healing time for placing the implants now falls outside the workflow as the implants are placed in the last step.
- ***Patient satisfaction***. The extremely long waiting time (healing phase) is eliminated.
- ***Flexibility***. The placement of normal implants and permanent prosthesis can be done by one appointment, which is more convenient for both dentist and patient.

Drawbacks:

- There are at least four appointments between patient and dentist.
- There are at least six times transportation between the dental lab and dentist side.
- Physical impression is still used in this situation.

2.8 Summary

This chapter described the main procedures of conventional dental implantation. Correspondingly, the Petri-net of the current dental workflow (AS-IS situation) and its redesigned model (TO-BE situation) are explained with a brief analysis of the benefits and drawbacks. There are two types of conventional dental implantations are discussed in this chapter, conventional crown replacement and conventional prosthesis replacement. The conventional crown replacement is applied to the patients with few missing teeth, and the whole procedure can be done with five phases which are intake phase, surgery phase, healing phase, abutment placement phase and final crown placement phase. Comparatively, conventional prosthesis replacement is adequate for the completely edentulous patients, and it also can be considered as a five-phase process. To be more specific, the first three phases in conventional prosthesis replacement are quite similar as those in crown replacement; however, the last two phases are very different. After that, the AS-IS situation models for both crown treatment and prosthesis treatment are described with detailed descriptions for each task. The main conclusions that achieved from the models are also given afterwards. Finally, one TO-BE situation models for crown treatment and two TO-BE situation models for prosthesis treatment are illustrated. For each TO-BE model, the main tasks, improvements, advantages and drawbacks are provided. The improved model make the whole procedure more efficient (e.g. time reduction) and flexible, and also increase the patients' satisfaction level, However, the number of times of appointments cannot be reduced, and the problem of time-consuming transportation for the crown still leaves unsolved.

Chapter 3

3. Research methodology

In this chapter, the research methodology of this project is presented. The first stage of the project is developing the promising TO-BE TO-BE dental workflow. After the completion redesigned dental workflow, the next step is to model it with modelling language of Petri-net in CPN tool [9]. After that, simulations of the TO-BE TO-BE model with gathered data will be achieved in CPN tool. At last, simulation result is evaluated and compared with the result from ITI project based on the key performance indicators. The main research procedures are concluded in the figure as below.

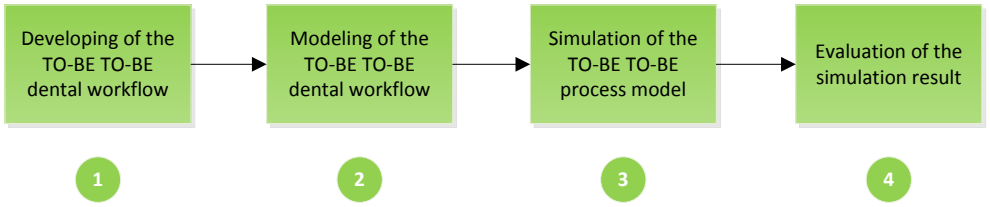


Figure 12, project procedure

3.1 Developing of the TO-BE TO-BE dental workflow

In general, the approach of developing the TO-BE TO-BE dental workflow can be divided into two phases, the redesign phase and the validation phase. The steps can be explained by the figure below.

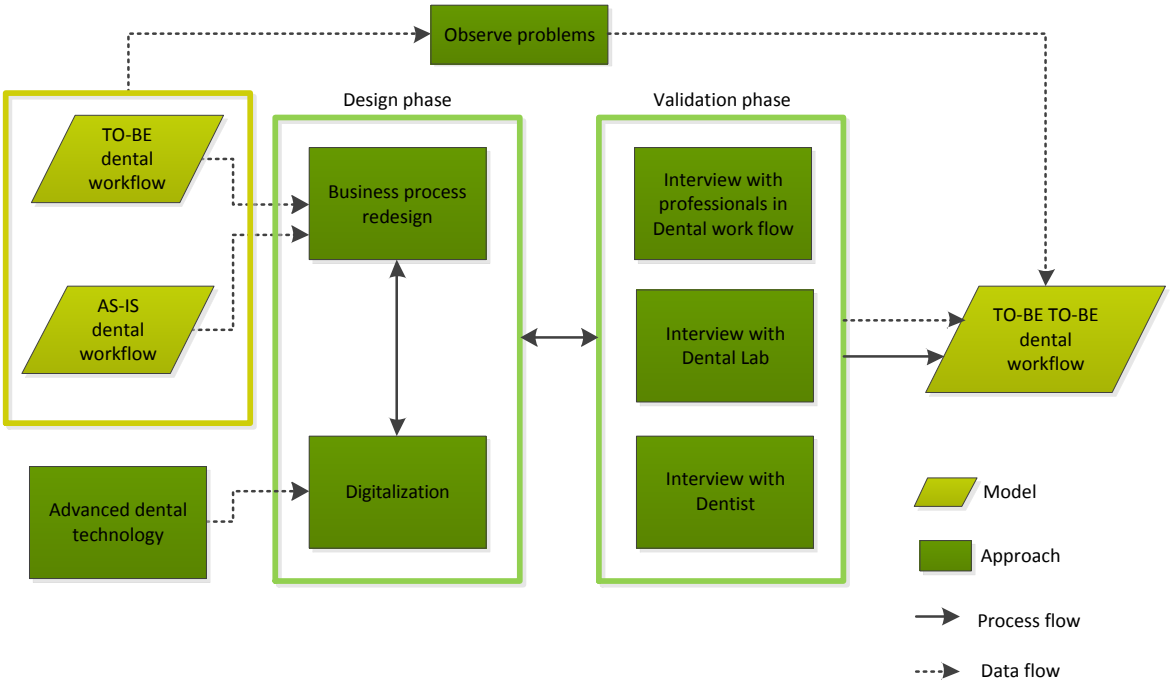


Figure 13, the approach of developing the TO-BE TO-BE dental workflow

In order to design the new dental workflow, the ideas and data are first collected from the AS-IS and TO-BE situation. After reviewing the previous models, we could get acquaint with current situation and have an in-depth understanding of the weakness of the current design. Based on this knowledge, we could start to redesign the dental workflow. The aim of the redesign phase is to design a number of

potential TO-BE TO-BE dental workflows. Therefore, only the previous knowledge is not sufficient, we also have to introduce some new and advanced dental technologies to come up some novel workflows. As showed in the figure 10, in the redesign phase, we will interactively approach the method of business process redesign and digitalization. Once a certain number of dental workflows are developed, all of them will be checked in the validation phase by dentist, dental technician and dental process expert. Repeating these two phases, an designed dental workflow will be finally validated by dental professionals and be selected. Furthermore, all problems observed from current AS-IS and TO-BE models are discussed after the simulation of TO-BE TO-BE model.

3.1.1 The idea in the redesign phase

Two approaches are adopted within the redesign phase, which are business process redesign and digitalization. Especially, based on the current dental workflow from ITI project (the AS-IS and TO-BE dental workflow), business process redesign is used to improve the developed workflow. Meanwhile, new ideas aiming to redesign the dental workflow will be come up with by literature review of digitalizing technique. As indicated above, the TO-BE dental workflows are the redesigned version of the AS-IS situation and were already developed in the ITI project. In this study, we aim to develop a promising TO-BE TO-BE dental workflow for the later future, which is the improved TO-BE dental workflow. Obviously, the TO-BE TO-BE dental workflow should be more advanced than the TO-BE situation. Then the first idea came up in our mind is to develop a redesigned version of the TO-BE situation. Therefore, a great understanding of the new added technology and redesigned process in the TO-BE situation is very crucial and should be in the first step.

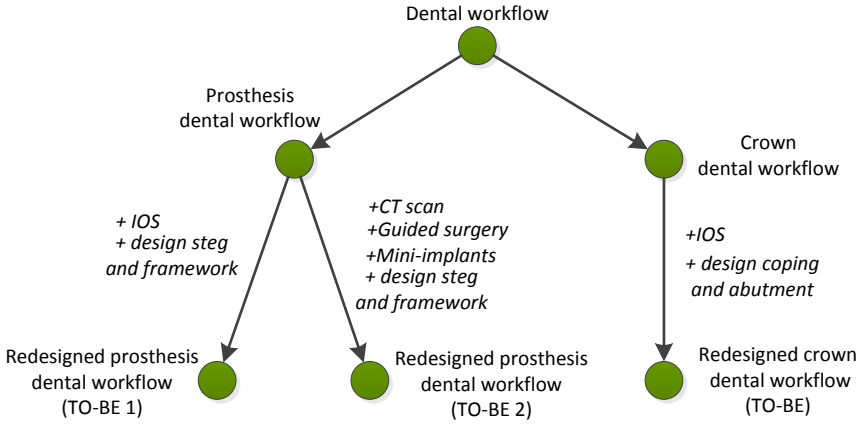


Figure 14, Review of the redesign method

As showed in the figure above, the TO-BE situation of crown treatment is redesigned by involvement of the IOS and designing steg and framework, and it is the same situation for TO-BE situation 1 of prosthesis treatment. From AS-IS situation to TO-BE situation 2 of prosthesis treatment dental flow, the technology of CT scan, guided surgery, mini-implants and designing steg and framework are adopted. Accordingly, in order to achieve the TO-BE situation, different new technologies are added on the basis of the AS-IS situation. Hence, a direct method for achieving TO-BE TO-BE dental workflow can be taken into consideration is to integrate multi-technologies that are used in the TO-BE situation. For example, an integration of the IOS and mini-implants might be a solution for reach TO-BE TO-BE situation. Obviously, IOS and mini-implants technologies that are used in the TO-BE situation are not the only new technologies available for developing TO-BE TO-BE dental flow. Any new potential technologies can be an option for achieving the TO-BE TO-BE dental workflow. The idea for designing TO-BE TO-BE dental workflow is conducted in the figure below.

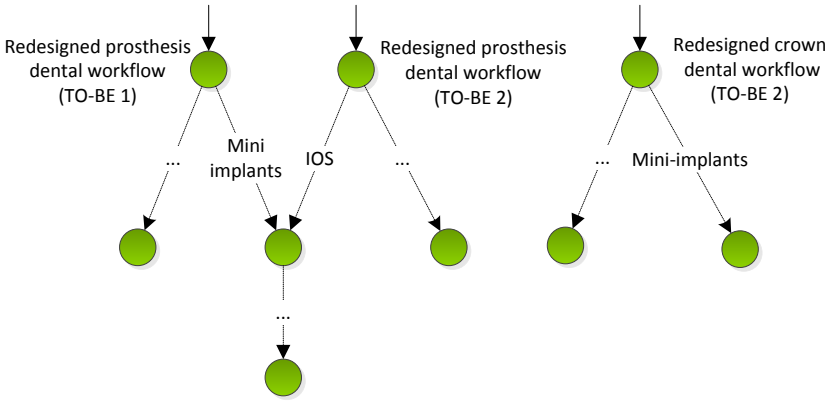


Figure 15, Developing direction of TO-BE TO-BE dental workflow

With this procedure, multiple redesigns will be developed and each of them is noted as a node in the tree (see figure above). For each node, an evaluation based on the devil's quadrangle will be provided and in the later validation phase according to the evaluation result only one node for crown or prosthesis treatment will be selected by interviewing dental professionals.

3.1.2 The idea in the validation phase

Be aware of that the redesigned process might not be acceptable in the point of view of dental professionals, we adopt the validation phase. The advices and ideas from dental professionals are the vital determinants of this study. During the validation phase, all the developed TO-BE TO-BE dental workflows will be checked and confirmed by dental experts to guarantee that the new dental workflow is practicable and acceptable for people work in dental value chain.

Therefore, a number of interviews are set up with dental professionals, such as prof. Daniel Wismeyer who are the dental expert in ACTA, Michiel Van Genuchten from Dental Wings, Ali Tahmaseb in ACTA and Patrick Oosterwijk in dental lab. During these interviews, we expect to receive feedback and advices regarding the redesigned models, and also collect some useful ideas regarding dental workflows from their aspect.

In the end, for the crown treatment, in total we developed three TO-BE TO-BE models, and only one of the three is passed the validation phase (the two failed models are given in appendix). For prosthesis treatment, we developed three models as well and only one of the three is passed the validation phase.

3.2 modeling of the TO-BE TO-BE dental workflow

The modeling language that be used to model the TO-BE TO-BE dental workflow is Petri Nets. The main reason that Petri Nets was chosen as the modeling language for this project is that the ITI project is also modeled by using Petri Nets. Furthermore, several characteristics of Petri Nets approach are quite suitable for this project. The detailed information will be indicated below.

The reasons that Petri Nets was chosen as the modeling language for this project are: According to the W.M.P. van der Aalst, "*Workflow processes are case-driven, i.e., tasks are executed for specific cases. These are marked by three dimensions: (1) the control-flow dimension, (2) the resource dimension, and (3) the case dimension*". Moreover: "*The control-flow dimension is the most prominent one, because the core of any workflow system is formed by the processes it supports. In the control-flow dimension building blocks such as the AND-split, AND-join, OR-split, and OR-join are used to model sequential, conditional, parallel and iterative routing*".[10] The book of "Three good reasons for using a Petri-net-based Workflow Management System" [11] clearly shows that the Petri net approach

meets the requirements of modeling of AS-IS situation and TO-BE situation. Specially, the ITI project is also modeled by using Petri Net approach.

3.3 Simulation of the TO-BE TO-BE process model

3.3.1 Data gathering

The input data, such as waiting time and execution time, plays a very important role in the process modelling. Without the real data, the model cannot be sufficiently simulated. To gathering data, two approaches are adopted in this study. One approach is to extract all the available data from the ITI project. The data in the ITI project are mainly from the following companies.

***Dental Practice Wilhelminaweg*:** The dental practice Wilhelminaweg (*http://www.tpwdieren.nl*) is a medium sized private dental practice in the Netherlands. Here, several experienced dental specialists and implantologists are working. The dental practice has a clinical management system in which all appointments are saved that have taken place for a patient. [12]

***Academisch Centrum Tandheelkunde Amsterdam (ACTA)*:** The ACTA is a collaborative venture involving the Faculties of Dentistry at the University of Amsterdam and VU University Amsterdam. In the department of Oral Implantology and Prosthodontics experienced implantologists are working as well as dentists that are educated in order to become an implantologist. For all patients that are treated, in the clinic management system, all the appointments and their timing are stored. [13]

***Dental Lab Zutphen*:** The Dental Lab Zutphen (*http://www.ttlzutphen.nl*) is a medium sized dental lab in the Netherlands. Amongst others, the lab takes care of the entire process of implant borne restorations such as crowns on implants and a prosthesis on implants. The lab has a dedicated lab management system in order to track all the products that are made in the lab. For each product that is made, it is stored which steps are performed and their timing. [14]

Dental Wings: Dental Wings (*www.dental-wings.com*) is a dental institution founded in Montreal, Canada. It provides innovations CAD/CAM solutions designed to improve the quality of dental restorations and increase productivity of dental laboratories and clinics. Dental Wings has already deployed their main dental software-Dental Wings Open Software in (DWOS) over 30 countries and 12 languages. Its development team is still dedicatedly working on improving DWOS and develop new software and modules.[15]

Another approach is to gather data via interviews with dental professionals. The personnel we interviewed include dentist (e.g. Daniel Wismeyer), dental technician (e.g. Patrick Oosterwijk) and dental workflow expert (e.g. Michiel Van Genuchten).

3.4 Evaluation of the simulation result

In order to evaluate the redesigned dental workflow, devil's quadrangle [1] is used as the framework of the evaluation where there are four different dimensions: time, cost, quality and flexibility. The idea is to describe the trade-off underlying every redesign measure, and to identify how each criterion from the devil's quadrangle can be made operational. Among the four dimensions, the dimension of time is chosen as the main performance indicator and will be given a quantitative evaluated. This reason behind this choice is that time is the most significant and direct-viewing factor to measure the benefits and efficiency of the TO-BE TO-BE model. Furthermore, it is also a relatively factor that can be used to give a fair comparisons with ITI project, since only time is quantify factor in ITI. On the aspects of other dimensions, an theoretical analysis will be addressed. To give the theoretical analysis, a definition for each dimensions are given as below.

Table 2, definition of the dimensions on different level of impact

Dimensions	*Impact level*	*Definition*
Time		The total throughput time of the dental treatment from the first intake to the final treatment.
	+ +	More than 10% time reduction of the total throughput time.
	+	More than 1% time reduction of the total throughput time.
	0	Less than 1% time reduction or addition of the total throughput time.
	-	More than 1% time reduction of the total throughput time.
	- -	More than 10% time addition of the total throughput time.
Cost		As the limitation of the data, it is not possible to give an evaluation on aspect of the total amount of the cost through the treatment. In this case, we concentrate on the three sub dimensions which are human resources, dental materials and instrument tools. Normally, the cost for each task is consist of the amount that spend in those three sub dimensions. Therefore, the number of sub dimensions that will lead to an addition or reduction on cost spending is evaluated here.
	+ +	Cost reduction on two aspects of the human resources, dental materials and instrument tools
	+	Cost reduction on one aspect of the human resources, dental materials and instrument tools
	0	No cost reduction/addition on aspects of the human resources, dental materials and instrument tools
	-	Cost addition on one aspect of the human resources, dental materials and instrument tools
	- -	Cost addition on two aspects of the human resources, dental materials and instrument tools.
Quality		The percentage of digitalization and automation in the whole treatment process.
	+ +	Addition of the task that is totally digitalized and automatic.
	+	Addition of the task that is partially digitalized and automatic which means a involvement of human is still necessary.
	0	Addition or elimination of any manual task. For most cases, the elimination/addition of a manual task is caused by the addition/elimination of a digitalized or automatic task and which is already considered in the positive/negative level, therefore the addition or elimination of any manual task will be considered as neutral.
	-	Elimination of the task that is partially digitalized and automatic.
	- -	Elimination of the task that is totally digitalized and automatic.
Flexibility		The quality of a process to deal with both foreseen and unforeseen changes in the context or environment it operate is the flexibility [16]. In the dental process, one of the most important factors that dental professionals concentrate on is the flexibility of resource. The ability to react on the changes on the resource for each task is evaluated here.
	+ +	More than two resources could execute on the additional task.
	+	Two resources could execute on the additional task.
	0	The resource of the additional or eliminated task is not able to change.
	-	Two resources could execute on the eliminated task.
	- -	More than two resources could execute on the eliminated task.

3.5 Summary

The goal of this chapter is to describe the research methodology of this project. The whole research procedure can be divided into four parts. Every step is set up based on the result of the previous step to ensure that each part is closely connected with each other and consistency of the whole process. The promising TO-BE TO-BE model can be developed based on the idea that integrates multi-new technologies used in the TO-BE model. A figure also is drawn to help better understand the idea of the redesign process. In terms of the modelling language, Petri-nets approach is very suitable for this project as the ITI project is also modelled with Petri Nets. The main data sources for this project come from ITI project and several dental institutions. Besides, doing interviews with dental professionals is another way for gathering data. After that, the model will be simulated in the CPNtools. The last steps of the research is to evaluate the simulation results.

Chapter 4

4. Process Model

In this chapter, the details of the two selected TO-BE TO-BE models will be presented. Especially, for each modification, an evaluation based on dimensions of time, cost, quality and flexibility will be shown. Furthermore, a theatrical analysis is adopt for further improvement and understanding of the models.

4.1 Overview of the redesigned crown treatment (TO-BE TO-BE situation)

The main objective of this section is to provide detailed explanation of the process in TO-BE TO-BE situation (crown treatment). The detailed process of TO-BE TO-BE dental flow (crown treatment) will be indicated in the first place, and a digital workflow will explained after that. Then, the main modifications will be given based on the AI-IS model. Finally, a theoretical analysis will be presented.

4.1.1 The dental process

After the redesign phase and the validation phase, the final TO-BE TO-BE dental workflow of crown treatment is developed, which is showed as the figure below.

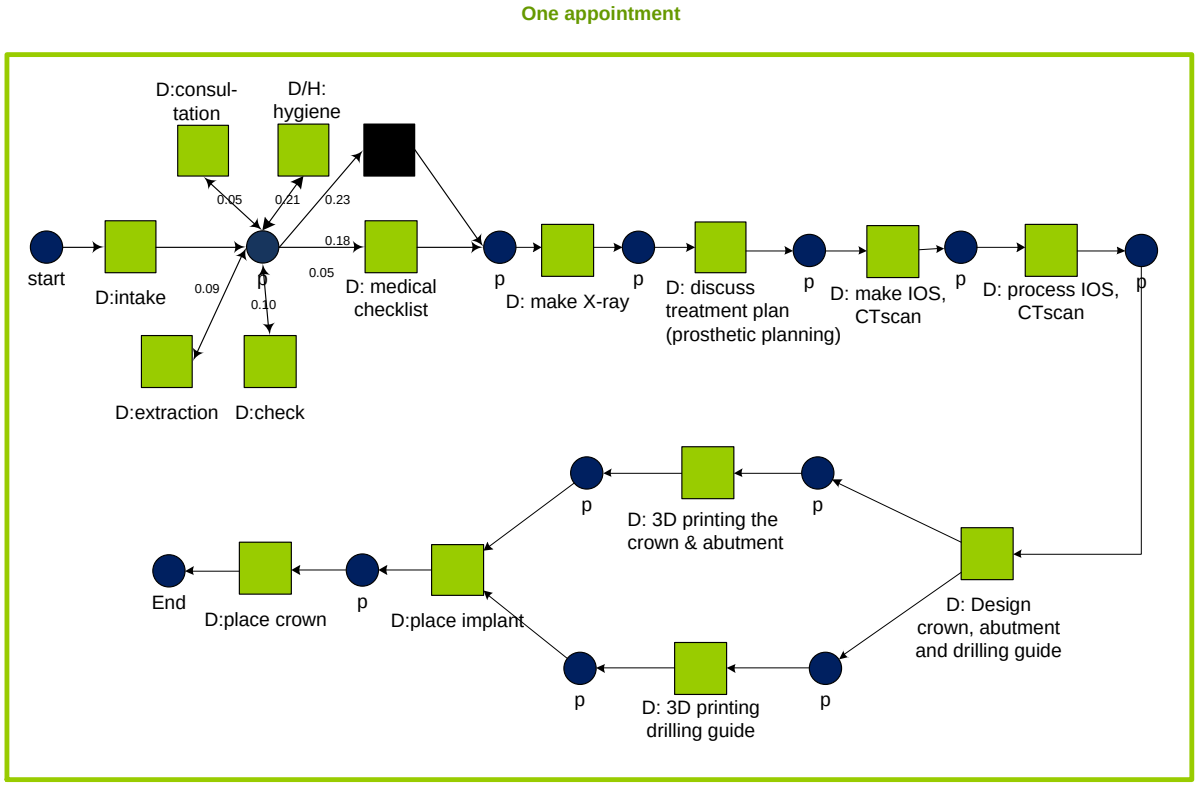


Figure 16, the process of one stop treatment

The main idea is that the tasks, such as intake, production and surgery etc, could all be performed within one day, which is named as the "one stop treatment" process or in short "OST". The content of each task in the model will be explained as follows:

Medical checking and preparation phase.

- **Intake**: In the first intake, dentist will get acquainted with the current situation of the patient. In other words, the appropriate type of treatment for the patient will be confirmed. After

taken all aspects into account, dentist will provide advices to his/her patient regarding the treatment and might briefly explain the procedures of specified treatment. Then, dentist will have a sufficient discussion with patient on the relevant information about the treatment. After that, the intake task is complete.

- **Consultation**: In case that the inquiry during the intake is not sufficient, an extra meeting will be set up between patient and dentist for exchange extra information.
- **Hygiene**: Normally, this task will be done by the registered dental hygienist. The normal procedures performed by hygienists include cleanings such as prophylaxis, scaling and root planning for patients with periodontal disease, taking of prescribed radiographs, dental sealants, administration of fluoride, and providing instructions for proper oral hygiene and care.
- **Extraction**: The target patients of this workflow are partial edentulous patient (missing one or several tooth). In some cases, patients lost their teeth by physical damage, thus some broken root of the teeth are still lie down in the gum tissue. A small surgery for extracting the broken teeth is executed in this task.
- **Check**: In the preparation of the treatment, the medical and dental history of the patient will be checked.
- **Medical checklist**: A comprehensive dental examination is adopted to guarantee that the treatment is safe and suitable for the patient.

Treatment planning.

- **Make X-ray**: After the medical checking and preparation phase, patient are able to receive the treatment. At this point, the X-ray or other medical imaging technology could be adopted during this task. The medical image will be the basis and support for generating the detailed treatment plan.
- **Discuss treatment plan**: At this step, a comprehensive treatment plan is generated and will be discussed with the patient. To some extent, dentist could even simulate an expected treatment result by software.

Surgery planning.

- **Make IOS and CT scan**: Both IOS and CT scan are executed in this task. Intra oral scanning is used to replace the impression and CT scan is used to determine the position for implants.
- **Process scan**: After the completion of IOS and CT scan, all the digital data are integrated for generating the virtual model of the patient.
- **Design crown and abutment**: With the virtual model, dentist could digitally place the implants, abutments and crowns.

On site Producing.

- **3D printing**: According to the virtual designing, the crown and abutments could be produced or printed by the 3D printer with the special powder.
- **Make drilling guide**: With the same idea as designing and printing of crown, the drilling guide will be designed based on the virtual placement of implants and will be produced in 3D printer.

Surgery execution.

- **Place implant**: Implants are in stored, thus the only thing that the dentist need to do is to select the implant according to the virtual planning and place it with the drilling guide.
- **Place crown**: Finally, the crown and abutment will be directly attached onto the implant.

Treatment complete.

4.1.2 Dental digital flow

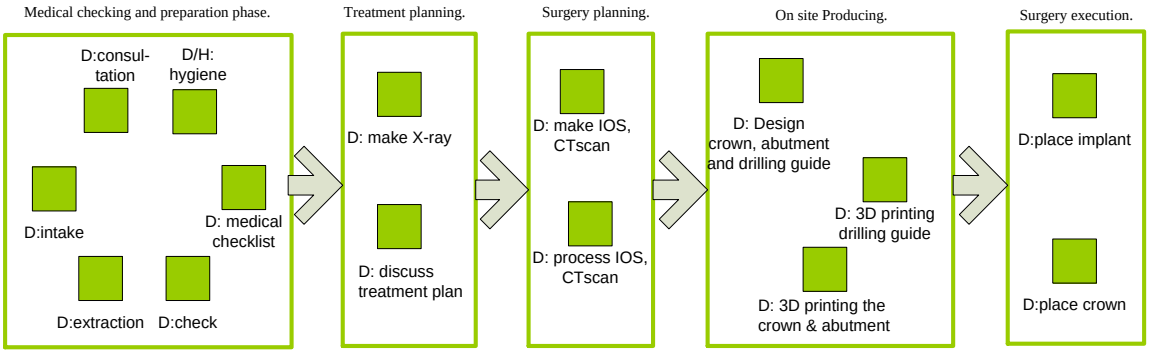


Figure 17, dental digital workflow of crown treatment

In the OST, all the steps are become digitized. As showed in the figure above, every phase is set up based on the digital result of the previous phase, and the digital result of each phase will be the key input for the next phase. For example, during the medical checking and preparation phase (the first phase), all patients' essential information will be recorded into the database. Once all the essential information is recorded, treatment planning could be start. Meanwhile based on the basic information from first phase and the result of x-ray from the second phase, dentist could confirm the treatment planning. With the treatment planning, IOS and CT scan are made as an input for the designing of the crown in production phase and the guided surgery in the surgery phase. In sum, each step within the process can be digitized.

4.1.3 Modifications from AS-IS situation to OST

In this section, all the process modifications from the conventional crown replacement (AS-IS situation) to the redesigned crown replacement (OST) will be described. Meanwhile, the reasons of modification and the benefit for the redesigning will be also stated. The main reason that the AS-IS model is chosen as the benchmark is AS-IS model is the basal model, OST is developed original from AS-IS model. Moreover, the AS-IS model stands for the current situation of dental flow.

1. Resequence the task: Discuss treatment plan

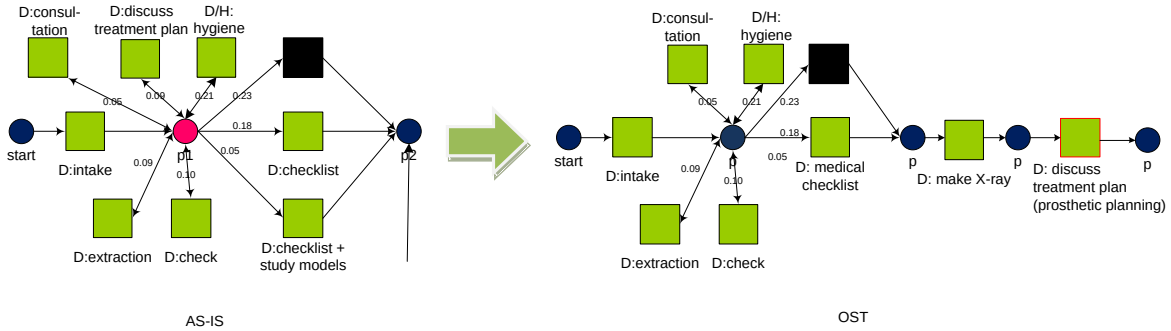


Figure 18, Resequence the task: Discuss treatment plan

Actually, in the current situation, discussing treatment plan is a very crucial and useful task for patient. Through discussing treatment plan, patients could get acquainted with the whole process of the treatment and the optional treatment method, thus they could make better decisions on receiving/refusing the treatment or choosing the treatment solution such as fix implantation or removable denture. However, in many cases, discussing treatment plan is ignored or simplified and integrated into the first intake because it has no impact on the result of the treatment. Therefore, in the AS-IS model, the task of "discuss treatment plan" is an option task after intake. However, the task of "discuss treatment plan" become a compulsory task in the OST model on behalf of patients' interests, since it is an assistant information for the decision making of the patient. Meanwhile, the modification is validated and strongly recommended during the interview with the dental expert, Ali Tahmaseb, in ACTA.

Table 3, impact of Resequence the task: Discuss treatment plan

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Resequence the task: Discuss treatment plan	Time	0	In AS-IS model of crown treatment, we already know from the ITI project in average it will take around 231 days for the whole treatment. Therefore, 1% of 231 days is 2.3 days and 10% of 231 days is 23.1 days. In this modification, the waiting time is eliminated due to the one appointment. Although the waiting time is around 9 days, the execution probability (0.09) is quite small and in average it will only take 0.81 days. Therefore, the addition of time is less than 1% of the total throughput time.
	Cost	-	Cost addition on resource of dentist since the optional task of dentist is modified to compulsory task.
	Quality	0	No addition or elimination of task.
	Flexibility	0	No addition or elimination of task.

2. Task elimination: checklist and study model

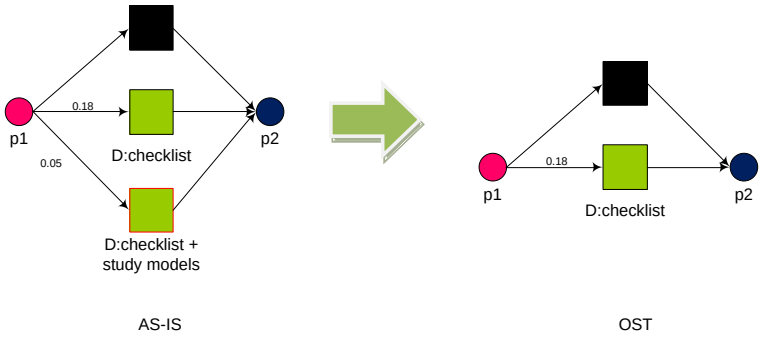


Figure 19, Task elimination: checklist and study model

The task of "checklist + study model" consists of the task of checklist and the task of study model. In the AS-IS situation, patients at place, "p1", have three alternatives to reach the next place and which option will be chosen will be decided with their dentists. Dentists will judge the fitness of the task based on the collected information of their patients from early phase. In most cases, empty task is selected since medical checklist is not necessary for most of patients. The task of "study models" is executed as a complement of the "discuss the treatment plan" task. During the task of "study models", dentist will use the custom dental model to explain the potential treatment solutions for the easy

understanding. The task of "study model" is eliminated since in the OST the new developed imaging technology is adopted. Based on the imaging information of patients, dentist could build the virtual models, thus the fabricated model will not be used any more.

Table 4, impact of Task elimination: checklist and study model

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Task elimination: checklist and study model	Time	0	Although the waiting time (around 17 days) of the task is eliminated, the probability (0.05) for executing the task is quite small. In average, it will only take 0.85 days.
	Cost	+ +	Cost reduction on resource of dentist and material of study model.
	Quality	0	Elimination of a manual task.
	Flexibility	0	The eliminated task can only be finished by dentist.

3. *Integral technology: make X-ray*

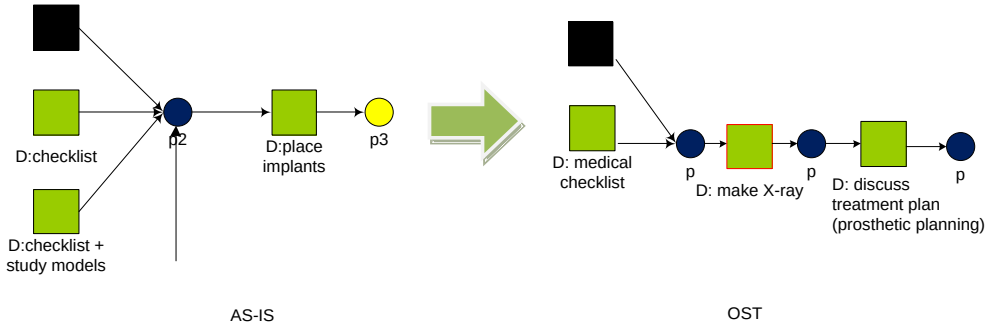


Figure 20, Integral technology: make X-ray

As indicated above, the task of "study models" is eliminated in the OST; hence, an corresponding new task with the same function should be added into the process. X-ray is one of the widely used medical imaging techniques and it is currently used by many prosthesis professionals for creating virtual models of the patient's body or parts. Especially, a certain number of software are being developed for translating the result of x-ray to the virtual model. Even though this technology is still not mature, but in the next five to ten years it will be become an very convenient and effective way to replace the fabricated dental model.

Table 5, impact of Integral technology: make X-ray

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Integral technology: make X-ray	Time	0	The impact is regarded as neutral because the execution time of the X-ray is less than 15 minutes and there is no waiting time.
	Cost	- -	Cost addition on resource of dentist and instrument tool for medical imagining of X-ray.
	Quality	+	Additional task is regarded as partial digital task.
	Flexibility	+	The additional task can be finished by dentist and X-ray technician.

4. *Elimination of the task: check-up*

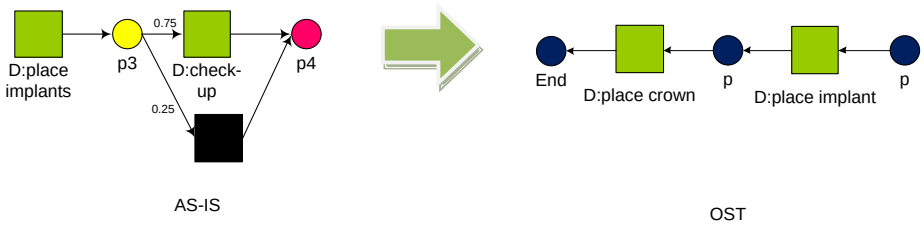


Figure 21, Elimination of the task: check-up

In many cases, once the implants are placed into the patient's mouth, a check-up of the implants are executed to guarantee the quality of the implant placement. Implants are the root for the fabricated crown, thus the failure of the implant placement will lead to big problems of the final crown placement. Hence, through the task of "check-up", in case that there probably one or some implants that are not placed in the right position, dentist can give a quick response immediately. However, in OST, the use of drilling guide is able to eliminate the human errors, thus the task of "check-up" can be eliminated.

Table 6, impact of Elimination of the task: check-up

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Elimination of the task: check-up	Time	0	With 0.25 execution probability, the waiting time and execution time is around 0.7 days (2.75days*0.25).
	Cost	+	Cost reduction on the resource of dentist.
	Quality	0	Elimination of a manual task
	Flexibility	0	The eliminated task could only be done by dentist.

5. *Elimination of the task: D/H:hygiene*

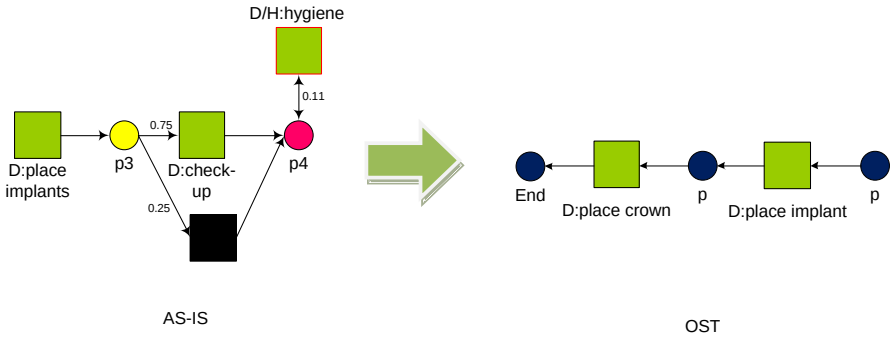


Figure 22, Elimination of the task: D/H:hygiene

After implant placement and corresponding check-up, the patient may need one or several times of hygiene for cleaning the placed implants during the healing time. For some patients, the regular hygiene is necessary to protect the placed implants. In the TO-BE TO-BE situation, the crown replacement could be finished within one appointment, so the hygiene will not be used before final crown replacement.

Table 7, impact of Elimination of the task: D/H:hygiene

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Elimination of the task: D/H:hygiene	Time	0	The waiting time for hygiene is around 12.3 days and execution probability is 0.11. Thus, it is less than 1% of the throughput time.
	Cost	+	Cost reduction of resource of dentist or hygienist.
	Quality	0	Elimination of a manual task
	Flexibility	-	The eliminated task can be finished by dentist and hygienist.

6. *Elimination of the task: Expose implant*

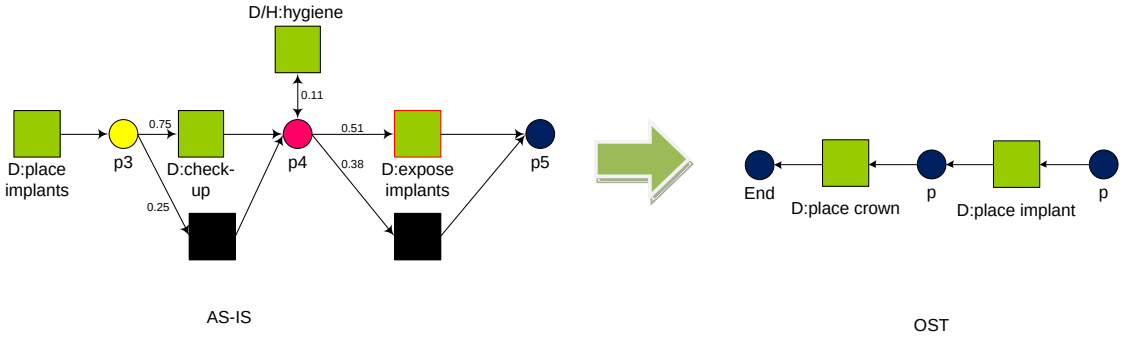


Figure 23, Elimination of the task: Expose implant

In AS-IS situation, after placing implants, there is a healing time about three to six months. After healing, the implants are underneath the gum tissue, thus the implants should be exposed in order to place abutment or crown. However, In OST, the treatment is done by one appointment, hence, exposing implants is not necessary any more. Exposing implants is useless and it can be eliminated.

Table 8, impact of Elimination of the task: Expose implant

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Elimination of the task: Expose implant	Time	+	The waiting time for exposing implants around 21.2 days. In average, it will take 10.812 days (21.2 days * 0.51).
	Cost	+	Cost reduction on resource of dentist.
	Quality	0	Elimination of a manual task
	Flexibility	0	The eliminated task can only be done by dentist.

7. *Elimination of the task: make individual impression trays*

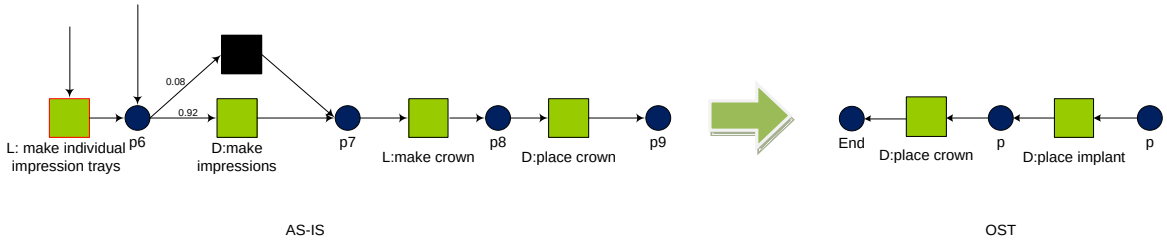


Figure 24, Elimination of the task: make individual impression trays

The individual impression tray is used to produce the individual impression, however, in OST the individual impression is digitalized and can be created by IOS at once. The complicated steps for producing the conventional impression tray can be eliminated.

Table 9, impact of Elimination of the task: make individual impression trays

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Elimination of the task: make individual impression trays	Time	+ +	The total execution time of this task is around 72 days.
	Cost	+ +	Cost reduction of dental technician and materials for the impression tray.
	Quality	0	Elimination of a manual task
	Flexibility	0	The eliminated task can only be done by dental technician.

8. *Elimination of the task: make impressions*

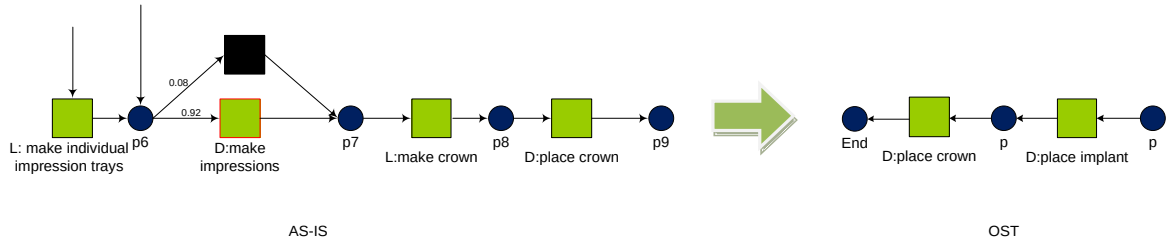


Figure 25, Elimination of the task: make impressions

In the AS-IS situation, impression is an appliance that is used to fabricate teeth model. Dental technician can create the crown for the patient according to the teeth model. However, due to the limitation of the materials used to produce impression, errors can be arisen during the producing process. In order to deal with this problem, physical impression is replaced by the IOS.

Table 10, impact of Elimination of the task: make impressions

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Elimination of the task: make impressions	Time	0	There is no waiting time for this task and the execution time is only range from 15 minutes to 60 minutes.
	Cost	+ +	Cost reduction on resource of dentist and materials for making impression.
	Quality	0	Elimination of a manual task
	Flexibility	0	The eliminated task can only be done by dentist.

9. *Integral technology: IOS and CT-scan*

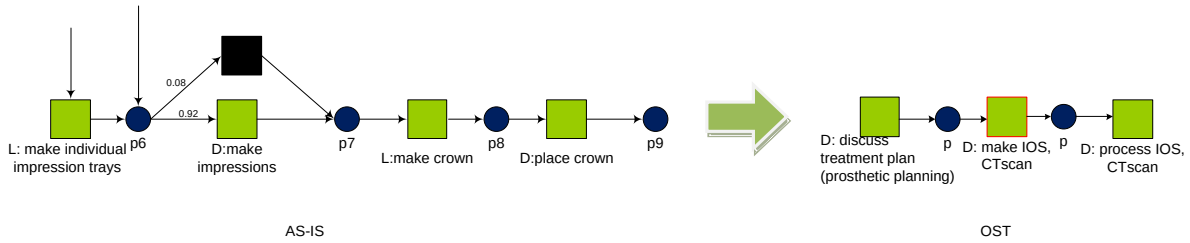


Figure 26, Integral technology: IOS and CT-scan

The main function of IOS is to generate a digital impression. One of the advantages of IOS is that it can be integrated with other digital output, such as X-Ray, CT scan and etc. The CT scan is added as IOS is only able to capture the impression of teeth, and CT scan is used to capture the jawbone structure of the patient. Hence, the integration of IOS and CT scan can present the complete information of the patient, and the result can be used to execute guided surgery.

Table 11, impact of Integral technology: IOS and CT-scan

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Integral technology: IOS and CT-scan	Time	0	The execution time is only range from 15 minutes to 100 minutes.
	Cost	- -	Cost addition on resource of dentist and instrument tool of intra oral scanner.
	Quality	+	Addition of a partial digital task.
	Flexibility	+	In terms of IOS, it can be finished by dentist or trained nurse. To CT-scan, it can be finished by dentist or CT-scan technician.

10. *Task automation: Process IOS and CT-scan*

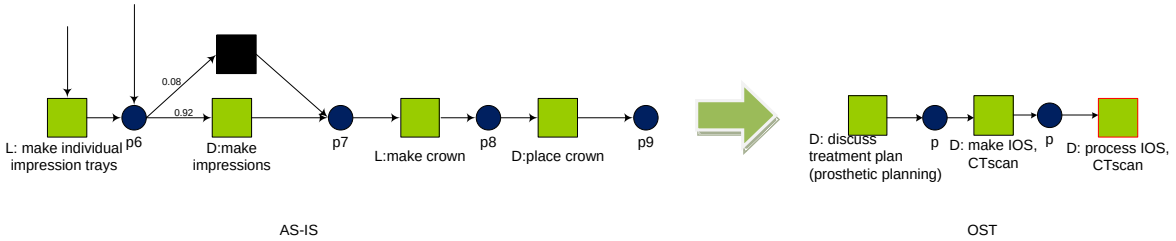


Figure 27, Task automation: Process IOS and CT scan

The results achieved from IOS and CT scan were recorded in the database and will be processed in this step. By simulation software, dentist could integrate the output of IOS and CT scan to generate an virtual model of the patient's mouth. With this virtual model, dentist are ready to do digital planning and designing.

Table 12, impact of Task automation: Process IOS and CT scan

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Task automation: Process IOS and CT scan	Time	0	The execution time is range from 12.88 minutes to 65.57 minutes.
	Cost	-	Cost addition on the instrument tool of the processing software.
	Quality	++	Addition of total digitalized and automatic task.
	Flexibility	+ +	This additional task can be done by any person who can manipulate the software.

11. *Elimination of task: make crown*

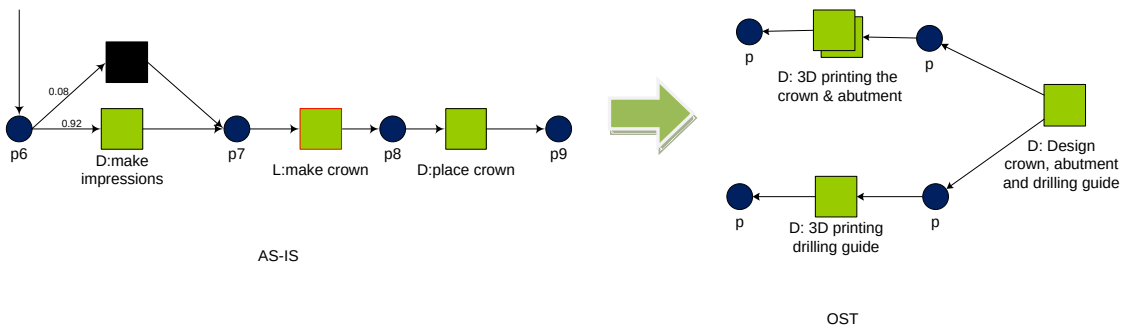


Figure 28, Elimination of task: make crown

In order to achieve the one stop treatment, all the tasks of dental lab should be eliminated. The conventional method for making crown is very time consuming and it consist of nine sub tasks which are "make plaster model implantology", "cut parts in plaster model", "place plaster model in articulator", "fixate plaster model for articulator", "make plaster model ready for designing the understructure", "design understructure crown using wax", "finalize understructure crown", "put opaque on crown" and "bake crown in oven". Once the crown is finished, people in dental lab will make an bill and transport the final product to dentist's office. Based on the information in the ITI model, in average the whole process will take around 17 days. The time consuming task has been replaced by the 3D printing and online designing in OST.

Table 13, impact of Elimination of task: make crown

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Task automation: Process IOS and CT scan	Time	+	17 days' time reduction
	Cost	+ +	Cost reduction on the resource of dental lab, materials for the plaster model.
	Quality	0	Elimination of an manual task.
	Flexibility	0	The eliminated task can only be finished by dental lab.

12. *Resource centralization: Design crown and abutment Addition of the task: design drilling guide*

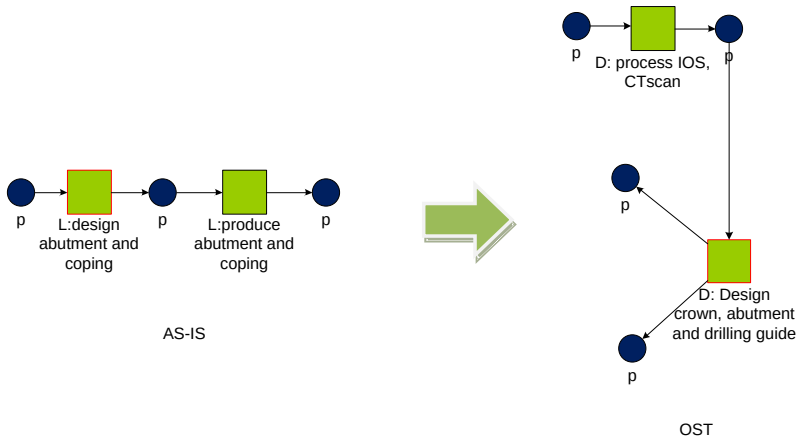


Figure 29, Resource centralization: Design crown and abutment; Addition of the task: design drilling guide;

In the AS-IS situation, the design of crown and abutment are done in the dental lab. However, in OST, a completed virtual model is generated by integration of IOS and CT results in previous step. It allows dentist to design crown and abutment by themselves. For the designing, there are some available templates in the designing software, dentist can revised or redesign these templates according to patients' situations. Hence, the crown and abutment design will be more simple and efficient in OST.

In terms of the drilling guide, it is a very crucial tool for the implants surgery. During the surgery, dentist needs to fix the drilling guide first, and all implants can be placed on the jawbone as planning by using drilling guide. Hence, it is unnecessary to raise the gum flap for exposing the jaw bone before the implants placement. In addition, drilling guide is able to help dentist place implant accurately. Correspondingly, the healing phase is eliminated, and the treatment can be completed within one appointment.

Table 14, impact of Resource centralization: Design crown and abutment; Addition of the task: design drilling guide;

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Resource centralization: Design crown and abutment Addition of the task: design drilling guide	Time	+	Around 2.8 days waiting time of design crown and abutment is eliminated and addition of around 11 minutes for designing drilling guide.
	Cost	- -	Cost addition on the resource of dentist for designing the drilling guide and the instrument tool of designing software.
	Quality	+	In terms of the designing of crown and abutment, no major modification on content of the task. In terms of designing drilling guide, it is an partial digitalized and automatic task.
	Flexibility	+	The designing can be done by dentist or dental technician.

13. *Integral technology: 3D printing*

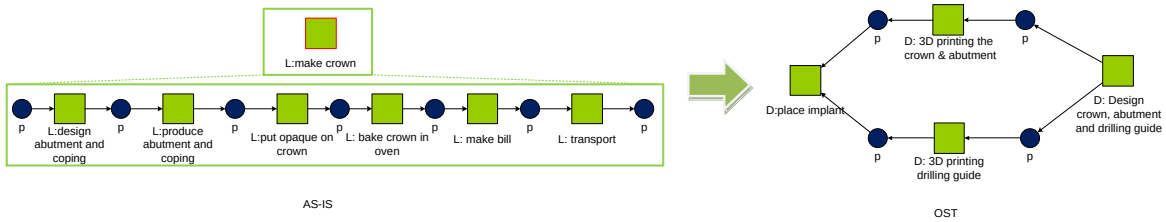


Figure 30, Integral technology: 3D printing

Crown and abutment fabrication is a quite time-consuming task in AS-IS situation as the products (e.g. crown, abutment and impression) need to transport between dentist side and dental lab for several times. In OST, all the crown and abutment are produced on site. Thus, transportation time is saved and one stop treatment becomes doable.

Table 15, impact of Integral technology: 3D printing

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Integral technology: 3D printing	Time	0	The average execution time for 3D printing is around 7 hours.
	Cost	- -	Cost addition on the instrument tool of 3D printer and materials of the printing powder.
	Quality	+ +	All the manual tasks are eliminated and the additional 3D printing is totally digitalized and automatic.
	Flexibility	+ +	The task can be done automatically.

14. *Resequencing the task: Place implant*

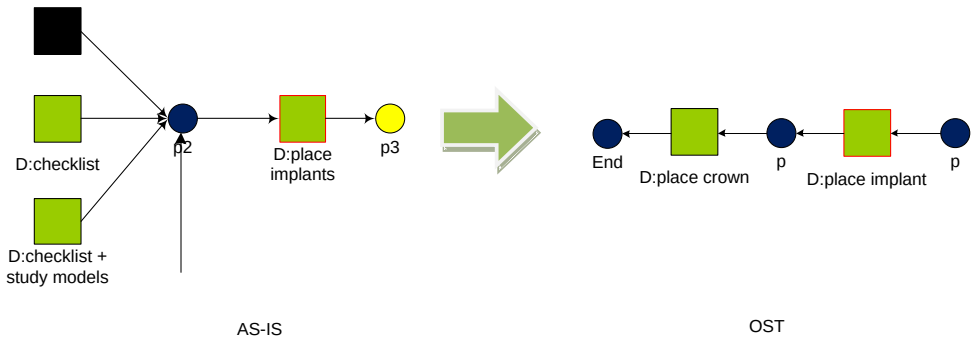


Figure 31, Resequencing the task: place implant

Placing implants are the first step of the surgery in the AS-IS situation, because dentist is able to design the abutment and crown on top of the implant only after implants are inserted into patient's mouth. However, in OST, placing implants can be performed in the last step, since we already designed the abutment and crown in the virtual model. And based on the designing, the drilling guide is fabricated for guarantee that the position of implants consist with the designing. The guided surgery is also performed during the surgery as a assistance in OST.

Table 16, impact of Resequencing the task: place implant

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Resequencing the task: place implant	Time	0	No time changes here.
	Cost	0	No cost addition or reduction.
	Quality	0	No changes on the content of the task, only the sequence is changed.
	Flexibility	0	No addition or elimination of task.

In general, OST can be concluded as a two-steps procedure, which are preparation and surgery. All the preparation, including surgery planning, crown production and etc., are finished at the first step. Then a one-time surgery is given to place all the implants, abutment and crown with the help of drilling guide and guided surgery in second step. In theory, an overall evaluation is listed as below.

Table 17, overall impact on time, cost and quality of all the modifications

Number	*Name of the modification*	*Time*	*Cost*	*Quality*	*Flexibility*
1	*Resequence the task: Discuss treatment plan*	*0*	-	*0*	0
2	*Task elimination: checklist and study model*	*0*	+ +	*0*	0
3	*Integral technology: make X-ray*	*0*	- -	+	+
4	*Elimination of the task: check-up*	*0*	+	*0*	0
5	*Elimination of the task: D/H:hygiene*	*0*	+	*0*	-
6	*Elimination of the task: Expose implant*	+	+	*0*	0
7	*Elimination of the task: make individual impression trays*	+ +	+ +	*0*	0
8	*Elimination of the task: make impressions*	*0*	+ +	*0*	0
9	*Elimination of the task: make crown*	+	+ +	*0*	0
10	*Integral technology: IOS and CT-scan*	*0*	- -	+	+
11	*Task automation: Process IOS and CT scan*	*0*	-	+ +	+ +
12	*Resource centralization: Design crown and abutment Addition of the task: Design drilling guide*	+	- -	+	+
13	*Integral technology: 3D printing*	*0*	- -	+ +	+ +
14	*Resequencing the task: place implant*	*0*	*0*	*0*	0
	Overall impact caused by the modifications	*5 plus Strong positive*	*1 plus Small positive*	*7 plus Strong positive*	*6 plus Strong positive*

As seen from the table, there is a strong improvement based on our definition of time, quality and flexibility. In terms of cost, the improvement is very limited. Therefore, the redesign provide an all-around improvement compared with the conventional process.

4.1.4 Theoretic review of the throughput time

In order to understand the OTS in quantitative aspects, the throughput time, which is a key performance indicator , is theoretically reviewed in this section. Based on the result from data gathering, all the waiting time and execution time are displayed as below.

Table 18, the quantitative value of waiting time and execution time

Task name	Expect Waiting time	Expect Execution time (minutes)	Execution probability	Resource
D: Intake	23.5 days	33.24	100%	Dentist
D: consultation	0.0	46.75675676	4.05%	Dentist
D: extraction	0.0	40.87837838	3.35%	Dentist
D: check	0.0	30	5.16%	Dentist
D: hygiene	0.0	35.08445946	9.03%	Dentist
D: medical checklist	0.0	30.30405405	4.46%	Dentist
D: make X-ray	0.0	12.5	100%	Dentist
D: discuss treatment plan	0.0	29.24710425	100%	Dentist
D: make IOS and CT scan	0.0	55.9122807	100%	Dentist
D: process scan	0.0	31.84663158	100%	N/A
D: design crown & abutment	0.0	20	100%	Dentist
D: 3D printing the crown & abutment	0.0	150	100%	N/A
D: design drilling guide	0.0	11.18	100%	Dentist
D: make drilling guide	0.0	270	100%	N/A
D: place implant	0.0	51.08108108	100%	Dentist
D: place crown	0.0	60	100%	Dentist
Total	23.5 days (33840 min)	574.1597492 (9.56 hours)	N/A	N/A

As showed in the table above, there is no waiting time for all the tasks except for intake, since we assume that within one appointment each task is scheduled and could be executed immediately after the completion of the previous one. The only exception in this case is intake because we consider that patients still need wait for weeks to receive the one stop treatment. The data sources of intake waiting time and all the execution time are from ITI projects or interviews with dental experts. Thus, in total, we could conclude that patients have to wait for around 23 days for the one stop treatment and the whole treatment will take around 9 hours and 33 minutes in total. In theory, all the tasks can be finished within one stop, however, in reality it does not work since the treatment will take 9 hours and 33 minutes which is more than the standard working hours (8 hours per day). Go through the whole treatment, we found that the tasks of producing drilling guide (in average 4.5 hours), crown and abutment (in average 2.5 hours) are the most time-consuming tasks. To reduce the time in these two tasks, the sequence of tasks execution is optimized. In OST, there are two alternatives to perform tasks (see figure below).

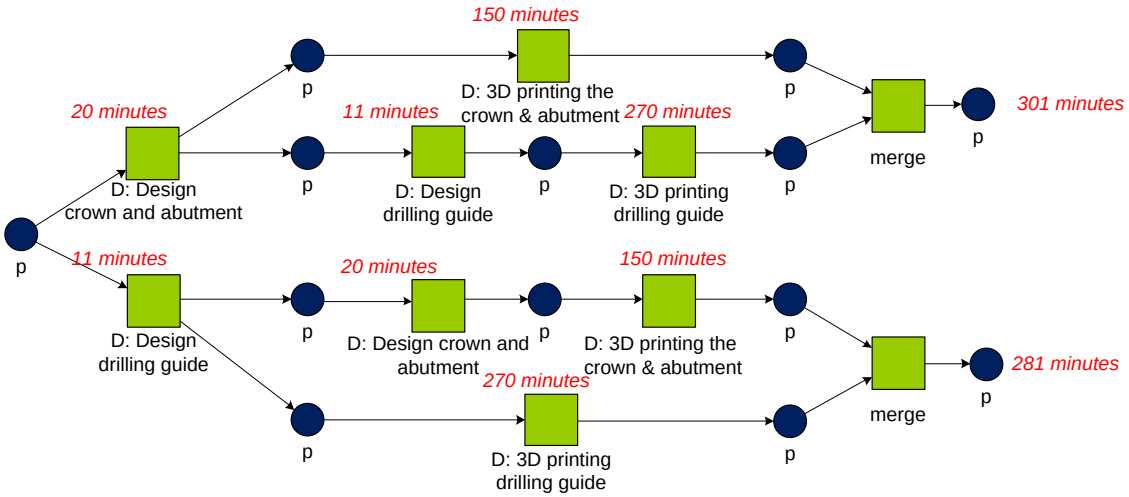


Figure 32, the quantitative insight of the processing time for producing drilling guide, crown and abutment.

As indicated in the figure, first performing the task of designing drilling guide will lead to a better result (281 minutes) than first performing the task of designing crown and abutment (301 minutes). Currently, the average execution time of these two alternatives is 291 minutes (301*0.5+281*0.5). Therefore, the OST can be optimized by first performing the task of "design drilling guide", then the average treatment time will be reduced by 10 minutes from 9 hours 33 minutes to 9 hours and 23 minutes.

In order to further cut down the treatment time, we expect a time reduction in the task of "3D printing the drilling guide". OST is expected to realize in five to ten years in the future, thus it is reasonable to estimate that 3D printing technology will be faster and reliable at that time. Here we assume 4 levels of time reductions which are cutting down 35%, 50%, 65% and 80% of the execution time for 3D printing. Based on the four time reductions, the 3D printing time for the drilling guide will take 175.5 minutes ($270\,minutes * (1 - 35\%)$), 135 minutes ($270\,minutes * (1 - 50\%)$), 81 minutes ($270\,minutes * (1 - 70\%)$) and 54 minutes ($270\,minutes * (1 - 80\%)$). For example of 35% time reduction, the time for performing the designing and producing of drilling guide, crown and abutment is 186.5 minutes ($175.5 minutes + 11\,minutes$). Therefore, the total treatment time will be reduced by 94.5 minutes from 9 hours 23 minutes to 7hours and 48.5 minutes. All the theoretical result are listed in the table below.

Table 19, the time reduction of 3D printing the drilling guide

Original expected time for printing drilling guide (minutes)	*Percentage of time reduction (minutes)*	*Reduced time for printing the drilling guide (minutes)*	*Total time for designing and printing of crown, abutment and drilling guide (minutes)*	*Reduced time for designing and printing of crown, abutment and drilling guide (minutes)*	*Total throughput time (hours)*
270	*35%*	*175.5*	*186.5*	*94.5*	*7.808333*
270	*50%*	*135*	*146*	*135*	*7.133333*
270	*65%*	*94.5*	*105.5*	*175.5*	*6.458333*
270	*80%*	*54*	*65*	*216*	*5.783333*

Based on this optimization and reduction, all the expect treatment time is less than 8 hours, and finishing the OST within one day can become realizable. (see table above)

Furthermore, there is a notice on the dentist's working time. Based on the theoretical data, the expected working time for dentist is 269 minutes. With strong request from dental professional, Ali Tahmaseb, we decide to add the tasks of X-ray and discuss treatment plan back for a more complete treatment. Thus those compulsory tasks in OST are not compulsory for AS-IS and TO-BE. In order to give a fair comparison with the previous models, it is more reasonable to compare the dentist's working time without the time of X-ray and discuss treatment plan with previous models. Then the new adjusted working time for dentist is 228 minutes ($269 minutes - 12 minutes - 29 minutes$).

4.2 Overview of the redesigned prosthesis treatment (TO-BE TO-BE situation)

In this section, a detailed introduction of the redesigned prosthesis treatment in TO-BE TO-BE situation will be given. Afterwards, the digital workflow will be explained for a better understanding of the digitalization in the process and the main modifications will be presented and evaluated by four dimensions. Also, there will be a theoretical analysis in the final place.

4.2.1 The workflow

Through the redesign phase and the validation phase, the most promising TO-BE TO-BE dental workflow of prosthesis treatment is selected and developed in Petri-net (see the figure below).

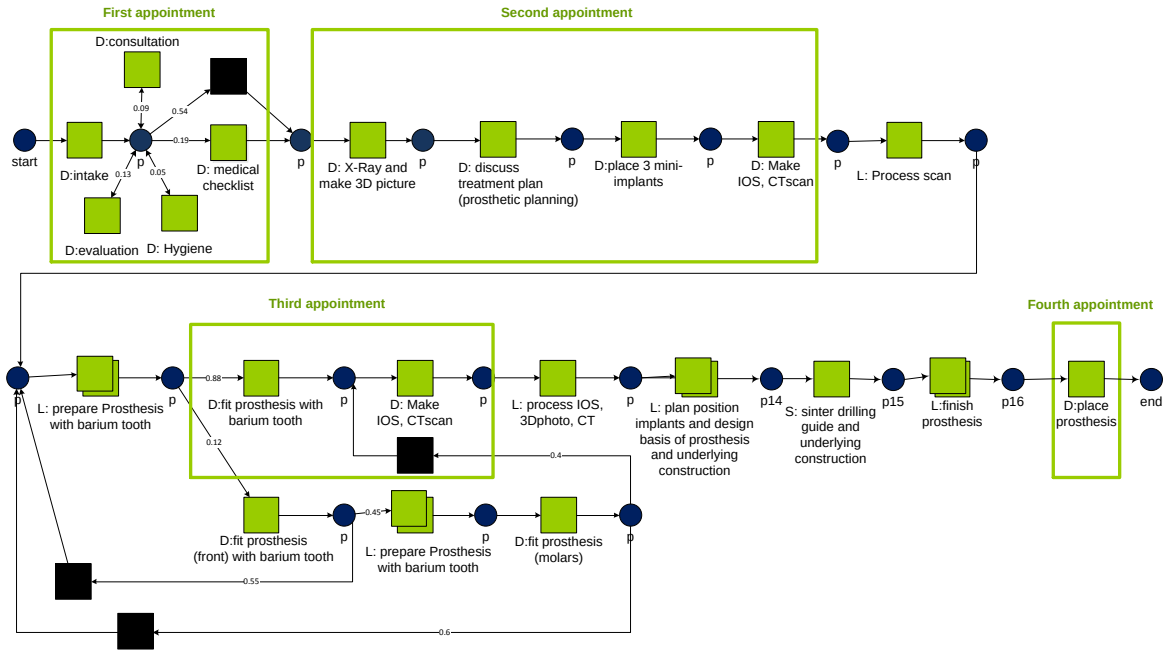


Figure 33, Digital Mini-implants Solution

The idea is to digitalize the entire value chain by introducing and fitting all the new technologies including mini-implants, 3D facial photo, guided surgery and etc. The perfect combination of the new digital technologies enables dentist to study patient's complete anatomy in detail, create surgery planning with less throughput time and place prosthesis in high precision. In general, the TO-BE TO-BE dental workflow is an optimized digital dental workflow, which is named as "Digital Mini-implants Solution" process or in short as "DMS" process in this thesis. In this section, we will first go through the DMS process by explaining the each task as showed in the Petri-net. Then, a description of the modifications comparing to the second TO-BE prosthesis treatment will be given. Finally, based on the Petri-net, a theoretic analysis is used to show an expected result of DMS process.

Generally speaking, the DMS process is performed in 4 main stages, diagnosis, mini-implant placement, prosthesis fitting and prosthesis placement. If the prosthesis is fitted into patient's mouth at one stop, then the whole process can be finished by four appointments that each stage is performed by one appointment (see figure above). Patients who are treated by DMS will go through the four main stages sequentially.

The first stage is diagnosis where all the basic information of the patient are collected and the healthy condition is evaluated. The detailed tasks in this stage are explained as below.

- ***Intake***: In the first intake, dentist will get acquainted with the current situation of the patient. In other words, the appropriate type of treatment for the patient will be confirmed. After taken all aspects into account, dentist will provide advices to his/her patient regarding the treatment and might briefly explain the procedures of specified treatment. Then, dentist will have a sufficient discussion with patient on the relevant information about the treatment. After that, the intake task is complete.
- ***Consultation***: In case that the inquiry during the intake is not sufficient, an extra meeting will be set up between patient and dentist for exchange extra information.
- ***Hygiene***: Normally, this task will be done by the registered dental hygienist. The normal procedures performed by hygienists include cleanings such as prophylaxis, scaling and root planning for patients with periodontal disease, taking of prescribed radiographs, dental sealants, administration of fluoride, and providing instructions for proper oral hygiene and care.[17]
- ***Evaluation***: In the preparation of the treatment, the medical and dental history of the patient will be checked.
- ***Medical checklist***: A comprehensive dental examination is adopted to guarantee that the treatment is safe and suitable for the patient.

At the beginning of the second stage, dentist will first make an X-ray and 3D picture for the patient which is used for creating a treatment plan. After discussion with the patient of the treatment plan, a small surgery for placing three mini-implants is performed by dentist. The tasks are explained as below.

- ***Make X-ray and 3D picture***: After the medical checking and preparation phase, patient are able to receive the treatment. At this point, the X-ray or other medical imaging technology is performed during this task. Meanwhile, a 3D photo is taken. The combination of the medical imaging and the 3D photo is processed by software to generate an 3D virtual model of the patient. This model will be the basis and support for developing a detailed treatment plan.
- ***Discuss treatment plan***: At this step, a comprehensive treatment plan is generated and will be discussed with the patient. Based on the virtual model generated by previous step, dentist could even simulate an expected result after treatment by software.
- ***Place 3 mini-implants***: Instead of placing all the implants, dentist only place 3 mini-implants into the jawbone with a triangular layout. This surgery is quite different from the one that place all the implants. In this case, it is not necessary to raise the entire gum flap for placing mini implants. Therefore, insertion of the 3 mini-implants is a flapless procedure and only 3 weeks is need before the placement of definitive implants.
- ***Make IOS and CT scan***: Both IOS and CT scan are performed in this task. Intra oral scanning is the digital impression and CT scan is used to show the structure of patient's the jawbone. Based on the combination of IOS and CT scan, dentist could design the position for implants with the planning software.

Between the stage of mini-implant placement and prosthesis fitting, all collected information from patient is delivered to the dental lab for fabricating the temporary prosthesis. In DMS, all the information collected in the previous steps is stored digitally, thus dentist only need to send all the required information via internet rather than physical transportation.

- ***Process scan***: After the completion of IOS and CT scan, all the digital data are integrated for generating the 3D virtual model of the patient.

- ***Prepare for fit of the prosthesis with barium crown***: In dental lab, dental technician will fabricate a temporary prosthesis to check the fitness. The whole procedure of fabrication consists of six sub steps (see figure below). Once the procedure is completed, the temporary prosthesis with barium crown will be transported to the dentist office.

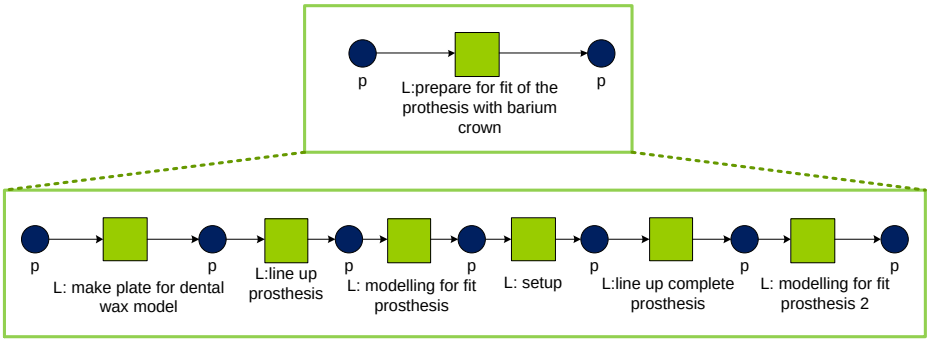


Figure 34, multi-tasks of "prepare for fit of the prosthesis with barium crown"

After arrival of the temporary prosthesis, dentist could start to check the fitness of the temporary prosthesis (third stage). Any unfitted temporary prosthesis will be sent back to the dental lab for additional adjustment.

- ***Fit prosthesis with barium tooth***: By adapting the temporary prosthesis, the fitness will be checked. The main idea is that the temporary prosthesis will be checked on aspects of suitability, aesthetics, function, shape and etc.
- ***Make IOS and CT scan***: If the prosthesis is suitable for the patient, then IOS and CT scan will be performed when patient wears the temporary prosthesis. The aim for making IOS and CT scan at second stage and this stage is different. At second stage, IOS and CT scan was made to generate an virtual oral toothless environment of the patient for producing the temporary prosthesis, and at this stage it is made for generating an virtual model where patient wears the temporary prosthesis. Based on this virtual model, dentist could design the position of permanent implants that support the prosthesis.
- ***Fit prosthesis (front) with barium tooth***: In some cases, patient is required to test the prosthesis (front) and molar separately. At this step, the fitness of the prosthesis (front) will be check. If it not fits, then at next step dental technician will be informed to reproduce an prosthesis (front). If it fits, then dental technician could start to produce the molar of the prosthesis at next step. Thus, in this case, there are at least two appointments at the third stage.
- ***Prepare for fit of the prosthesis with barium crown***: The prosthesis (molar) is produced in this step, which shares the same task with the producing an prosthesis.
- ***Fit prosthesis (molars)***: After arrival of the prosthesis (molars), the fitness of it is tested by patient. With the fitted one, the IOS and CT scan could be made afterwards. With the unfitted one, the dental technician is required to produce a new temporary prosthesis again.

After the completion of IOS and CT scan, all the digital data are sent to the dental lab for processing.

- ***Process IOS, CT scan and 3D photo***: As indicated before, IOS and CT scan are made where patient wear the temporary prosthesis. Thus, a new virtual oral model of the patient is created in this task by processing the combination of IOS, CT scan and 3D photo.
- ***Digital implant placement***: In simulation software, based on the generated virtual model, dental technician or dentist could design the ideal position of the implants that support the temporary prosthesis in a precise manner.

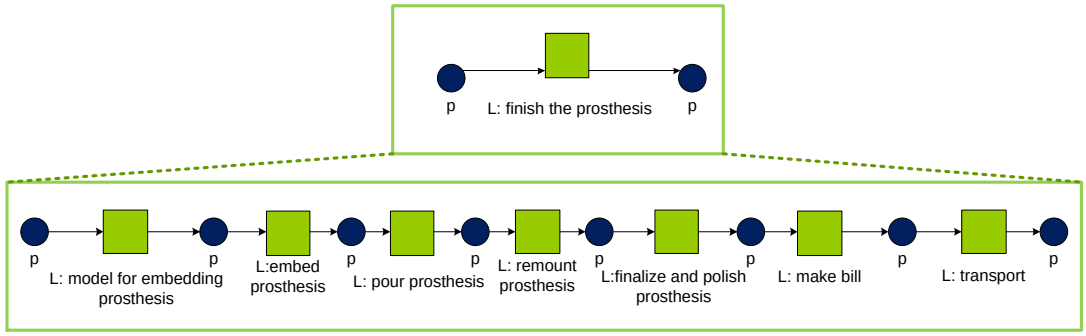
- ***Design basis of prosthesis and underlying construction***: With virtual model based on the use of IOS, CT scan, 3D images and computer processing. a digital and non-stereolithographic milled surgical guide using mini-implants as references to transfer the information from the computer to the patient is created. This 3D imaging protocol using templates attached to diagnostic transfer (mini-) implants enabled the dentist to digitally plan the treatment of a patient and to design and fabricate a surgical guide and eventually the definitive superstructure, to be placed at the time of surgery.
- ***Mill basis prosthesis and underlying construction***: After the completion of the designing, the designed drilling guide and superstructure are produced.
- ***Finish the prosthesis***: In this step, the final permanent prosthesis will be fabricated. Actually, it is not necessary to build the prosthesis from scratch. It can be made by duplicating the fitted temporary prosthesis and embedded it into the superstructure that produced before. After finalizing and polishing the prosthesis, it can be transported to the dentist's office.
- 

Figure 35, multi-tasks of "finish the prosthesis"

In the last stage (fourth stage), placing permanent prosthesis could be performed by dentist.

- ***Place prosthesis***: After the arrival of the permanent prosthesis, it is ready to start the final surgery for placement of implants and prosthesis. The surgical template was first connected to the mini-implants using screws. The drilling guide was extremely stable because of the good internal connection of the mini-implants and their triangular distribution. The drilling sequence was executed for each implant starting with the punch and ending with the last drill through the template. Then the implants were inserted using the specified implant driver. The procedure was repeated for each implant in the toothless jaw. After the placement of the last implant, the surgical template was removed by unscrewing the screws. Immediately after insertion of the implants, the definitive restorations were screwed directly at the implant level without interlocking any abutments. The mini-implants were removed by reverse torqueing. The fit was evaluated by panoramic radiography and the occlusion was checked. Minor occlusal adjustments were carried out.

4.2.2 Dental digital flow

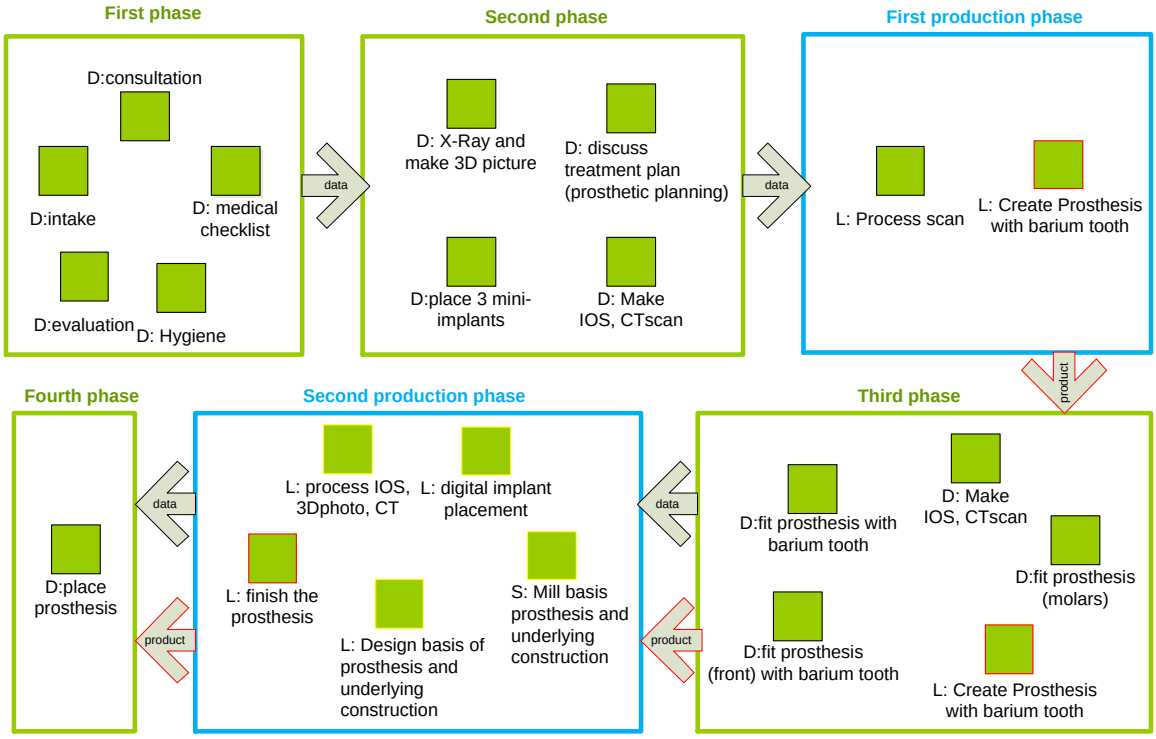


Figure 36, dental digital workflow of prosthesis treatment

Although the workflow of DMS is not totally digitalized like OST, the interaction between connected phases is greatly simplified by digitalization. As showed in the figure above, after the first phase (similar to the medical checking and preparation phase in OST), all patients' essential information was recorded and sent to the second phase where combination of data from first phase and result of medical imaging is used to create treatment plan. All the data from second phase will be delivered to dental lab for processing and creation of temporary prosthesis. Afterwards, temporary prosthesis is transported to the third phase for the fitness checking and this is the only part of no data flow. Some additional transportation of the unfitted prosthesis may happen here. Then, the fitted prosthesis will be directly transported to second production phase for producing final prosthesis. Meanwhile, the data of the medical imaging is also flowed into this phase for digital planning of the positions of implants. In the end, the permanent prosthesis is finished and transported to the fourth phase while all the required data is flowed into final phase for the guided surgery. All phases will consume data from previous phase and generate new data for the next phase except the output of first production phase and the input of third phase. In general, we can state that the entire value chain is partially digitalized.

4.2.3 Modifications from TO-BE situation to DMS

The idea in developing the DMS is combining and fitting the novel technologies from the two TO-BE situations. Mini-implants as a brand new concept is introduced in one of the TO-BE situation, in the DMS we still share an same main structure with this mini-implants' process. As the DMS is redesigned based on the TO-BE situation 2 with new technologies such as mini-implants etc., the TO-BE situation 2 will be selected as benchmark in this case.

Therefore, all the modifications from the TO-BE dental workflow (based on mini-implants) to the DMS will be described. Meanwhile, the reasons of modification and the benefit for the redesigning will be also stated.

1. *Resequencing the task: Discuss treatment plan*

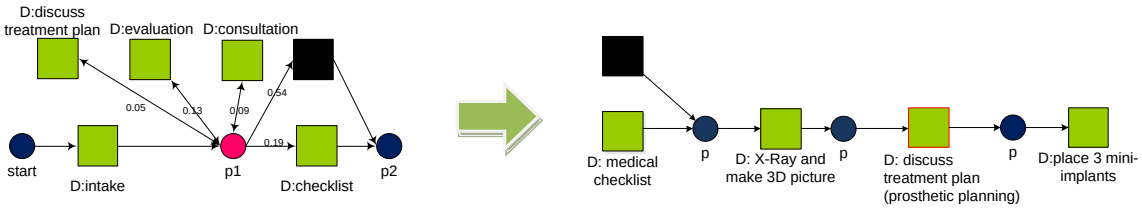


Figure 37, Resequencing the task: Discuss treatment plan

As indicated in the OST part, discussing treatment plan is a very crucial task for patient to make better decisions on receiving/refusing the treatment, thus we want to resequence this task from an optional task to a compulsory task. In addition, the task is performed prior to placing 3 mini-implants, because on the one hand we consider that the discussion of treatment plan should occurred before any surgery and on the other hand the planning may guide the placement of 3 mini-implants in an precise manner.

Table 20, impact of Resequencing the task: Discuss treatment plan

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Resequencing the task: Discuss treatment plan	Time	+	In the TO-BE 2 model of the prosthesis treatment, we already know from ITI project in average it will take around 172 days. Therefore, 1% of 172 days is 1.72 days and 10% is 17.2 days. In this case, the waiting time is totally eliminated since in each appointment there is no waiting time between adjacent task. The waiting time was range from 76.8 days to 163.296 days in TO-BE 2, but the execution probability is quite small (0.05). Thus, in average, the waiting time range from 3.84 days to 8.16 days, which is longer than 1.72 days but shorter than 17.2 days, is eliminated.
	Cost	-	Cost addition on the resource of dentist since the optional task of dentist is modified to compulsory task.
	Quality	0	No addition or elimination on digital or automatic task.
	Flexibility	0	No addition or elimination of task.

2. *Addition of task: Hygiene*

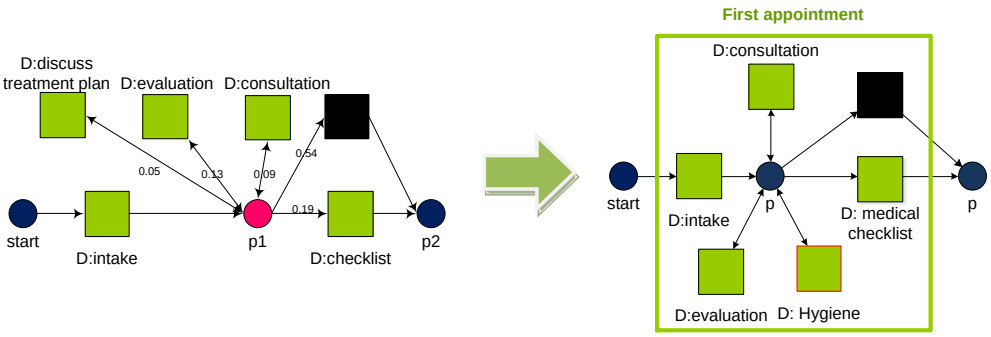


Figure 38, Addition of task: Hygiene

There is no hygiene task in the TO-BE situation for the basic or advanced cleaning. In the DMS, we believe that a certain level of cleaning is very important for keeping the treatment safe. Similar to

OST, this task will be done by the registered dental hygienist or dentist. The normal procedures performed by hygienists include cleanings such as prophylaxis, scaling and root planning for patients with periodontal disease, taking of prescribed radiographs, dental sealants, administration of fluoride, and providing instructions for proper oral hygiene and care.

Table 21, impact of Addition of task: Hygiene

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Addition of task: Hygiene	Time	0	The average execution time of hygiene is around 35 minutes.
	Cost	-	Cost addition on resource of dentist or hygienist for the task of hygiene.
	Quality	0	Addition of an manual task.
	Flexibility	+	The additional task can be done by dentist and hygienist.

3. Addition of task: make X-Ray and 3D picture

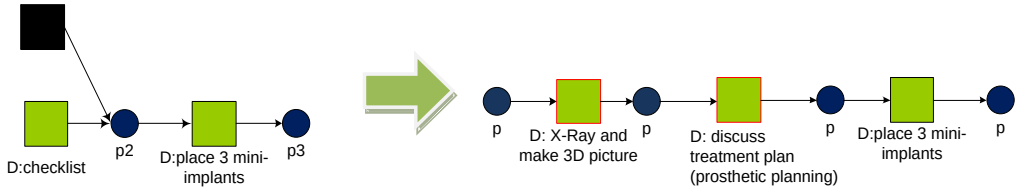


Figure 39, Addition of task: make X-Ray and 3D picture

As the discussion of the treatment plan becoming compulsory, X-ray is added for generating a more detailed planning. Especially, a certain number of software are being developed for translating the result of x-ray to the virtual model. With the virtual model, it will become a very convenient and effective way to create treatment plan and show the ideal treatment outcome. In addition, the 3D picture is taken because the patient is edentulous. For edentulous patient, their bone will resorb or atrophy when there is no tooth root to stimulate the bone. Bone resorbtion can lead to serious changes in facial appearance, thus 3D picture is taken for watching the facial appearance. In later steps, the 3D picture could also be used for designing the prosthesis in simulation software.

Table 22, impact of Addition of task: make X-Ray and 3D picture

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Addition of task: make X-Ray and 3D picture	Time	0	The waiting time of this task is same with placing 3 mini-implants (see appendix for details) and the waiting time of 3 mini-implants is eliminated. Therefore, in total there is no changes on the waiting time. The average execution time is 25 minutes.
	Cost	- -	Cost addition on resource of dentist and instrument tool for medical imagining of X-ray.
	Quality	+	Addition of partial digitalized task.
	Flexibility	+	Making X-ray can be done by dentist and X-ray technician. Making 3D photo can be done by dentist and any others.

4. *Integral technology: Make IOS and CT scan*
Task elimination: individual impressions, prepare registration bite, register bite

Figure 40, Integral technology: Make IOS and CT scan; Task elimination: individual impressions, prepare registration bite, register bite

IOS is used to generate a digital model of the patient's oral environment. The CT scan is added since IOS is only able to capture the impression of teeth, and CT scan is used to capture the jawbone structure of the patient. Hence, the integration of IOS, CT scan and previous 3D picture can present the complete information of the edentulous patient, and the result can be used to execute guided surgery.

In addition, individual impression is eliminated because it shares the same function with IOS and IOS is said to be faster and less exhausting for both dentist and patients compared the use of impression. Similarly, IOS can also be used for generating a virtual model of the patient's bite. Thus, both of the tasks can be eliminated.

Table 23, impact of Integral technology: Make IOS and CT scan; Task elimination: individual impressions, prepare registration bite, register bite

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Integral technology: Make IOS and CT scan; Task elimination: individual impressions, prepare registration bite, register bite	Time	+ +	In total, the execution time of the eliminated task is around 139.2 days. And the added execution time in average is only around 67 minutes.
	Cost	+	There is a cost addition on the resource of dentist for making IOS and CT scan and instrument tool of the intra oral scanner. Meanwhile, there is also a cost reduction on resource of dentist or dental technician for make individual impression, prepare registration bite and registering bite, medical materials for making impression. In total, the number of ways leading a reduction of cost is more than one of addition.
	Quality	+	Elimination of several manual tasks and addition of partial digital task.
	Flexibility	+	All the eliminated tasks can only be done by dentist. In the additional task, the IOS can be done by dentist or trained nurse and the CT-scan can be done by dentist or CT-scan technician.

5. *Task automation: Process IOS, 3D picture and CT scan*

Figure 41, Integral technology: Process IOS, 3D picture and CT scan

The results achieved from IOS, CT scan and 3D picture were recorded in the database and will be processed in this step. By simulation software, dental technician could integrate the output of IOS, CT

scan and 3D picture to generate an virtual model of the patient. With this virtual model, dental technician are ready to do digital planning and designing.

Table 24, impact of Task automation: Process IOS, 3D picture and CT scan

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Task automation: Process IOS, 3D picture and CT scan	Time	0	The waiting and execution time of the task is 1.25 days.
	Cost	-	Cost addition on the instrument tool of the processing software.
	Quality	+ +	Addition of a total automatic and digitalized task.
	Flexibility	+ +	The additional task is totally automatic, so it can be triggered by anybody.

In general, DMS is redesigned by introducing the technologies from TO-BE 1 (such as IOS) and TO-BE 2 (such as the mini-implants and guided surgery). All the technologies are suitably utilized and organized in DMS with at least four appointments. Each replacement of new technology will lead to a reduction on the waiting time, especially the waiting between dentist's side and dental lab is greatly decreased. Meanwhile, with the addition of digitalized tasks in the process, the human error and errors happened in the transportation will be minimised. However, the cost dimensions will be increased due to additional usage of resources, purchasing the new materials and introduced new instrument tools. Furthermore, the flexibility of resources in the process is generally improved. In theory, an overall evaluation is listed as below.

Table 25, impact on time, cost and quality of all the modifications in DMS

Number	*Name of the modification*	*Time*	*Cost*	*Quality*	*Flexibility*
1	*Resequence the task: Discuss treatment plan*	+	-	*0*	*0*
2	*Addition of task: Hygiene*	*0*	-	*0*	+
3	*Addition of task: make X-ray and 3D photo*	*0*	- -	+	+
4	*Integral technology: Make IOS and CT scan* *Task elimination: individual impressions, prepare registration bite, register bite*	+ +	+	+	+
5	*Task automation: Process IOS, 3D picture and CT scan*	*0*	-	+ +	+ +
	Overall impact caused by the modifications	*3 plus Strong positive*	*4 minus Strong Negative*	*4 plus Strong positive*	*4 plus Strong positive*

4.3 Theoretic analysis

In order to understand of the DMS in a quantitative aspect, the throughput time, which is a key performance indicator, is theoretically reviewed in this part. Based on the result from data gathering, all the waiting time and execution time are calculated as below.

Table 26, the analysis of expect waiting time and execution time

Task name	Waiting time (days)	Execution time(minutes)		Resources	Execution probability
		Experienced	Inexperienced		
Intake	20.5800	57.5000	53.5714	Dentist	100%
evaluation	0.0000	17.6471	20.0000	Dentist	13%
hygiene	0.0000	26.6667	50.6250	Dentist	5%
consultation	0.0000	19.6250	39.3750	Dentist	9%
checklist	0.0000	30.0000	35.2174	Dentist	19%
make x-ray and 3D photo	53.6736	25.0000	25.0000	Dentist	100%
Discuss treatment plan	0.0000	30.0000	33.0000	Dentist	100%
place 3 mini-implants	0.0000	54.3750	54.3750	Dentist	100%
make CT scan	0.0000	15.0000	15.0000	Dentist	100%
make IOS	0.0000	35.2143	83.5714	Dentist	100%
process IOS and CT scan	0.0000	1800.0000	1800.0000	N/A	100%
make plate for dental wax model	7.4971	15.0000	15.0000	Dental technician	100%
line up prosthesis	0.0000	16.0000	16.0000	Dental technician	100%
modeling for fit prosthesis	0.0000	3.0000	3.0000	Dental technician	100%
setup	2.912	26.0000	26.0000	Dental technician	100%
line up complete prosthesis	0.0000	26.0000	26.0000	Dental technician	100%
modeling for fit prosthesis_2	0.0000	16.0000	16.0000	Dental technician	100%
transport	0.0000	1800.0000	1800.0000	N/A	100%
fit prosthesis	0.0000	33.0000	33.0000	Dentist	90%
fit prosthesis (front)	0.0000	30.0000	30.0000	Dentist	10%
fit prosthesis (molars)	0.0000	30.0000	30.0000	Dentist	82%
do preoperative planning + segmentation	3.5047	7.0900	7.0900	Dental technician	100%
design steg + structure	0.0000	11.1800	11.1800	Dental technician	100%
sinter drilling guide and steg	0.0000	5040.0000	5040.0000	Milling center	100%
model for embedding prosthesis	2.3720	11.0000	11.0000	Dental technician	100%
embed prosthesis	0.0000	3.0000	3.0000	Dental technician	100%
pour prosthesis	0.0000	11.0000	11.0000	Dental technician	100%
remount prosthesis	0.0000	6.0000	6.0000	Dental technician	100%
finalize and polish prosthesis	0.0000	21.0000	21.0000	Dental technician	100%
make bill	0.4648	2.0000	2.0000	Dental technician	100%
transport	0.0000	1800.0000	1800.0000	N/A	100%
place prosthesis	0.0000	120.0000	120.0000	Dentist	100%
Total	87.2810 days (125684.64min)	7.7395 days (11144.88 min)		N/A	N/A
Total throughput time	95.0205 days (136829.52 min)			N/A	N/A

Based on the data above, we can give a quantitative check of the model. As indicated before, the whole treatment could be done by at least four appointments. The first appointment is started from intake and stopped before making x-ray. According to the table, patient will wait for about 20 days for the first intake and this appointment will take about 2 hours in average. After that, normally patient will wait for about two and half months for the treatment. The second appointment will be started with taking X-ray and discussing the treatment plan, and the patient will receive the mini-implants placement surgery afterwards. This appointment will be completed after taking IOS and CT, and the whole procedure of the second appointment will take around 3 hours. Then, there will be a time gap around 6.3 days aiming to provides the efficient time for dental lab to produce the temporary prosthesis. The fitness of the temporary prosthesis will be done during the fourth appointment. If the temporary prosthesis is suitable and fitted, the patient will be taken a CT scan and IOS with the temporary prosthesis on. The fourth appointment will take 2 hours and 20 minutes in total. The permanent prosthesis will be produced based on the fitted temporary prosthesis by the dental lab. and this step will take 6.14 days. At last, the final dental surgery will take 2 hours during the last appointment.

4.4 Summary

The overview of the redesigned crown treatment and prosthesis treatment in TO-BE TO-BE situation is clear explained in the chapter. These two different treatments in TO-BE TO-BE situation are renamed as “OST” and “DMS” respectively. Basically, the whole dental process of OST is divided into 6 main steps, which are medical checking and preparation, treatment planning, surgery planning, on site producing, surgery beginning and treatment completed. There are several sub-steps within every main step. Regarding DMS, the division the whole procedure is based on the four appointment. The detailed explanation of each sub step in OST and each task within the appointment in DMS is given in the first place. After that, the digital work flow is introduced aiming to reflect how the digital information effect OST and DMS process. Furthermore, the main modifications for OST and DMS will be given and discussed based on the AS-IS model and TO-BE (mini-implants) model respectively. The benchmark model selection depends on which model is the original model of OST and DMS. After that, there will be a discussion of drawbacks and benefits of each modification based on the devil’s quadrangle. To be specific, we will discuss the drawbacks and benefits from 4 different dimensions, which are cost, quality, time and flexibility. Accordingly, from both patient and dentist aspects, the conclusion derived from OST show that the total time is reduced and the quality level is increased but the cost is also increased to because of the introduction of the new technology. Besides, the flexibility level is increased for dentist but decreased on patient’s side. Correspondently, in DMS, time, quality level and flexibility level are increased, while the cost is increased on dentist aspect and unclear on patient aspect. Finally, a theoretical analysis about OST and DMS is set up in order to receive a direct viewing of the time distribution of the redesigned model and check if there are any potential improvements of the process.

Chapter 5

5. Simulation Experiments

Once the process models for both crown placement and prosthesis placement are developed as described in chapter 4, the next step of the research is to build the simulation models. In order to give a fair comparisons with the previous models in ITI project, all the basic setup in this simulation model is in line with ITI project. The construction of the simulation model will be presented, and also how it meets our needs will be explained afterwards. With the simulation, it was possible to investigate the quantitative impacts of redesigned dental workflow. Two quantitative simulation models were build that captures the workflow of crown replacement and the workflow of prosthesis placement in the TO-BE TO-BE situation.

5.1 Basic Setup in ITI

In order to understand and analyse the model in detail, we should first clear the assumptions or design decisions that have been made.

Assumptions on time.

1) In this model, the time unit is assumed as minutes, thus almost every waiting time and execution time of treatment is computed by minutes.
2) To some tasks, the time unit is day. For example, some waiting time will be long by days, so the time unit of it is day.
3) a mode of 24 hour clock (real time strategy) is used in the model
4) office hours is range from 9 ‘o clock till 17 ‘o clock, so in total there are 8 working hours per day except weekend. However, the time unit in the CPN model is minute, hence, the time unit need to be transferred from hour to minute in this model. The following table shows that time structure of time in this model. For instance, based on the information in the first column, the working hours is from 9:00am to 17:00pm on Monday, thus the 9:00 is transferred to 540th minutes and the 17:00 is transferred to 1020th minutes. In other words, the working hours is from 540th minutes to 1020th minutes on Monday in the simulation model.

Table 27, working time per week in the model

	Monday	*Tuesday*	*Wednesday*	*Thursday*	*Friday*	*Saturday*	*Sunday*
	0:00 (0 min)	0:00 (1440 min)	0:00 (2880 min)	0:00 (4320 min)	0:00 (5760 min)	0:00 (7200 min)	0:00 (8640 min)
	9 hours (540 minutes)						
Working time Begin	9:00 (540 min)	9:00 (1980 min)	9:00 (3420 min)	9:00 (4860 min)	9:00 (6300 min)		
	8 hours (480 minutes)						
Working time End	17:00 (1020 min)	17:00 (2460 min)	17:00 (3900 min)	17:00 (5340 min)	17:00 (6780 min)		
	7 hours (420 minutes)						
	24:00 (1440 min)	24:00 (2880 min)	24:00 (4320 min)	24:00 (5760 min)	24:00 (7200 min)	24:00 (8640 min)	24:00 (10080 min)

5) The waiting time or execution time in the model are all calculated based on office hour. Hence, time which elapses outside office hours is not taken into account.
6) The waiting time or execution time in the model are generated by three methods which are continuous distribution, discrete distribution and constant.

7) For tasks that need to be performed during office hours, only office hour is considered. For example, if the waiting time is 90 minutes and the current time is 4.30 on Monday, then the task will be started at 10 ‘o clock on Tuesday.
8) For each treatment within one appointment, there is no waiting time.

Assumptions on patients:

1) Each patients has a unique identity number (ID), but without the name, since in our simulation the name of patients are not useful. The model will be more readable with less information.
2) The arriving time is also stored as the basic information of patients.
3) In our model, patients are not allowed to come back to receive the same treatment program again. Thus, once the treatment complete, the patient will leave the treatment and the ID number is stored.
4) The maximum capacity for the patients are 570 in the crown replacement and 420 in the prosthesis replacement.
5) The number of patients arrive in a given time (per day) follows the compound Poisson distribution. Arrival process can be captured by the compound Poisson distribution with $\lambda = 0.411$ in crown treatment $\lambda = 0.21787$ in prosthesis treatment.
6) patients may see different dentists and may also see the same dentist for multiple appointments after each other.

Assumptions on dentist:

1) For all the treatments within one appointment, the dentist will always be the same.
2) The dentists are classified as either experienced or inexperienced which has impacts on the duration of tasks done by them. For example, for the ‘intake’ task, the average duration, when done by an experienced dentist, is 21,3 minutes (standard deviation: 12,8 minutes) whereas for an inexperienced dentist this is 56,3 minutes (standard deviation: 11,0 minutes).

Assumptions on dental lab technician:

1) we assume that once a lab technician has started working on a task, he will be working exclusively on that task till it is completed.

Assumptions on process:

1) There are many places in the process where alternative paths can be taken. The probability of taking any path is depend on the experience level of previous dentist. Therefore, in the simulation model, the probability is made based on the previous task has been performed by an experienced or inexperienced dentist. An example which is from crown treatment is listed as below. As indicated above, after intake, there are several alternative paths, the experienced dentist and inexperienced dentist will have different probability distributions of the path selections.

$$if\ dentist\ is\ experienced,$$

$$then\ Next\ execution\ step\ is \begin{cases} \mathrm{D}_{\mathrm{extraction}} & prob \in (97,100](3\%) \\ \mathrm{D}_{\mathrm{consultation}} & prob \in (94,97](3\%) \\ \mathrm{DH}_{\mathrm{hygiene}} & prob \in (92,94](2\%) \\ \mathrm{h1} & prob \in (0,88](88\%) \\ \mathrm{D}_{\mathrm{check}} & prob \in (90,92](2\%) \\ \mathrm{D}_{\mathrm{checklist}} & prob \in (88,90](2\%) \end{cases}$$

$$if\ dentist\ is\ inexperienced,$$

$$then\ Next\ execution\ step\ is \begin{cases} \mathrm{D}_{\mathrm{extraction}} & prob \in (96,100](4\%) \\ \mathrm{D}_{\mathrm{consultation}} & prob \in (90,96](6\%) \\ \mathrm{DH}_{\mathrm{hygiene}} & prob \in (68,90](22\%) \\ \mathrm{h1} & prob \in (0,48](48\%) \\ \mathrm{D}_{\mathrm{check}} & prob \in (57,68](11\%) \\ \mathrm{D}_{\mathrm{checklist}} & prob \in (48,57](9\%) \end{cases}$$

Assumptions on execution of tasks:

1) Tasks can be performed by different kind of resources, such as dentist, dental lab technician and etc.
2) The duration time of executing an task is depends on two folds. One is the experience level of the dentist who perform the task. Other one is the number of implants that have been placed. For example, for the placing of one implant it takes on average 38,8 minutes (standard deviation: 23,1 minutes) by an experienced dentist whereas for two implants this is on average 64,6 minutes (standard deviation: 34,5 minutes) when done by an experienced dentist. This makes that for tasks done after implantation and the implantation itself, the duration is determined by a discrete probability distribution which has the number of implants and the experience of the dentist as parameters.
3) Some tasks are more likely to be done by experienced dentists and the other way around. For example, the 'fit prosthesis (front)' task is more often done by inexperienced dentists (22%) than experienced dentists (3%). Also, even if the dentist is experienced or inexperienced, the next task may generally be done by another experienced or inexperienced dentist. Therefore, for each next task done by a dentist, the probability is taken into account that another dentist than the previous one performs the task. If this is the case then additionally the probability is taken into account that there needs to be change from an inexperienced dentist to an inexperienced dentist, a change from an experienced dentist to an inexperienced dentist, or whether no change in experience is needed.

5.2 Performance indicators

Performance indicators can be used to measure the effects of the TO-BE TO-BE dental workflows. Generally, we are following the four dimensions of the devil's quadrangle, but due to the limitation of input data we will only give an quantitative result on the time dimension. From ITI project, we already collected the simulation result from AS-IS and TO-BE dental workflow on the following performance indicators.

Performance indicators from ITI:

- The throughput time of the entire process (the time from patient arrived in the workflow till the completion of the last task in the workflow)

- The time needed by the dentists to perform the tasks in the workflow (e.g. the sum of the duration of the tasks that are performed by a dentist)
- The time needed by the dental lab technicians to perform the tasks in the workflow, i.e., the sum of the duration of the tasks that are performed by a dental technician.

Except the performance indicators in ITI project, we are also interested in the waiting time and execution time for all the appointments in our TO-BE TO-BE dental workflow. The performance indicators are listed as below:

Additional performance indicators in this study:

- *Total waiting time for each appointment in the workflow*. Before each appointment, patients have to wait in the queue and the sum of the waiting time for all the appointments are defined as the total waiting time.
- *Total dental appointment time*. The sum of all the appointments time during the whole treatment. Especially for the unique appointment in OST, we would like to check whether it can be finished by one day, where the appointment time is defined as the time from patient's arrival at the dentist's office for the first intake until completion of the treatment. In this case, the appointment time is not considered the time that patients need to wait for the appointment.

Note that, based on the above definition, the sum of the total waiting time and total appointment time should be the same with the total throughput time.

5.3 Experiment result for OST

The result of performance indicators that were measured during the simulation are displayed as below. The simulated average value, 95% confidence interval, minimum value and maximum value of each indicators are shown in the following tables.

Total throughput time. Total throughput time is the duration starting from arrival of patients until the completion of the treatment. The simulation results show that the difference between average total throughput time under different time reduction on 3D printing is very small (less than 0.18%). The average total throughput time are range from 37498.084985 minutes (26.04 days) to 37569.821197 minutes (26.09 days). According to the theoretical result, the total throughput time is 23.82 days, which is about 2.2 days less than the simulation results.

Table 28, total throughput time with different time reduction on 3D printing

Time reduction	*Average(minutes)*	*95% Half Length(minutes)*	*Minimum(minutes)*	*Maximum(minutes)*
35%	*37569.821197*	*164.370569*	*2513.080000*	*119971.480000*
50%	*37500.842390*	*208.527691*	*2470.060000*	*120183.470000*
65%	*37498.084985*	*178.597170*	*2413.470000*	*120070.190000*
80%	*37540.410616*	*177.307395*	*2388.210000*	*120226.940000*

Dentist's working time. In the one stop treatment, for each patient, all the treatment process will be done by the same dentist. Thus, the dentist's working time is monitored here. Similar to the total throughput time, there is a very small difference on the dentist's working time with different time reduction level on 3D printing. The average dentist's working time is range from 277.609862 (about 4.63 hours) to 278.049124 (about 4.63 hours) according to the simulation results, which is 0.14 hours longer than the theoretical results.

Table 29, dentist's working time with different time reduction on 3D printing

Time reduction	*Average(minutes)*	*95% Half Length(minutes)*	*Minimum(minutes)*	*Maximum(minutes)*
35%	*278.049124*	*0.638097*	*123.610000*	*650.550000*
50%	*277.609862*	*0.625529*	*123.550000*	*634.100000*
65%	*277.861261*	*0.590980*	*123.920000*	*652.810000*
80%	*277.960647*	*0.577956*	*124.490000*	*641.910000*

Dental technician's working time. In one stop treatment, all the works are finished by dentist within one appointment, thus there is no working time for dental lab.

Additional performance indicators:

Total waiting time. All patients are expected to stay in a waiting list for several weeks before treatment (first intake). The waiting time that a patient waits for treatment is monitored here. The average total waiting time is range from 37048.8714845 minutes (around 25.7 days) to 37163.135095 minutes (around 25.8 days) based on the simulation result, while the theoretical total waiting time is 23.5 days. There is around 2.2 days difference when making the comparison.

Table 30, total waiting time with different time reduction on 3D printing

Time reduction	*Average(minutes)*	*95% Half Length(minutes)*	*Minimum(minutes)*	*Maximum(minutes)*
35%	*37077.676455*	*164.378610*	*2053.040000*	*119481.070000*
50%	*37048.871484*	*208.526803*	*2055.960000*	*119735.410000*
65%	*37084.978988*	*178.617669*	*2038.090000*	*119653.570000*
80%	*37163.135095*	*177.279535*	*2041.830000*	*119832.580000*

Throughput time of the appointment day *(exclude the total waiting time)*. As indicated before, all the patient should wait for the treatment for a couple of weeks, to observe the duration time of the treatment day, the throughput time of the treatment is monitored as the appointment time. The simulated average throughput time of the appointment day is greatly influenced by the time reduction on the 3D printing. It is range from 377.275521 minutes (around 6.29 hours) to 492.144741 minutes (around 8.20 hours) with 80% time reduction to 30% time reduction, and the theoretical value is 5.78 hours under 80% time reduction to 7.80 hours under 30% time reduction. The gap in between is less than 8.03%.

Table 31, the appointment time with different time reduction on 3D printing

Time reduction	*Average(minutes)*	*95% Half Length(minutes)*	*Minimum(minutes)*	*Maximum(minutes)*
35%	*492.144741*	*0.631649*	*329.330000*	*894.960000*
50%	*451.970906*	*0.643543*	*290.630000*	*840.950000*
65%	*413.105998*	*0.667619*	*253.120000*	*812.980000*
80%	*377.275521*	*0.633171*	*216.200000*	*781.440000*

Execution time of X-ray and discuss treatment plan. As indicated before, this simulated result is used to give a fair comparison in the evaluation.

Table 32, execution time of X-ray and discuss treatment plan with different time reduction on 3D printing

Time reduction	*Average(minutes)*	*95% Half Length(minutes)*	*Minimum(minutes)*	*Maximum(minutes)*
35%	*41.419242*	*0.056742*	*25.000000*	*59.990000*
50%	*41.445233*	*0.052047*	*25.000000*	*59.970000*
65%	*41.436613*	*0.054221*	*25.000000*	*60.000000*
80%	*41.402114*	*0.056529*	*25.000000*	*59.960000*

5.4 Experiment result for DMS

The result of performance indicators that were measured during the simulation of DMS are listed as below.

Total throughput time. Total throughput time is duration starting from the patient arrival until the completion of the treatment. The simulated result is 95.352643 days, which is around 0.3 days more than the theoretical result (95.0205 days) of total throughput time.

Table 33, the result of total throughput time

Average (days)	*95% Half Length*	*Minimum (days)*	*Maximum (days)*
95.325643	*0.385715*	*23.971313*	*236.722583*

Dentist's working time. In DMS, for each appointment, all the treatment tasks will be done by the same dentist. The dentist's working time is monitored here. The simulated result indicates that the average dentist's working time is around 8.3 hours (496.914378 minutes), while the theoretical dentist's working time (around 7.8hours) is 0.5 hours longer.

Table 34, the result of dentist's working time

Average (minutes)	*95% Half Length*	*Minimum (minutes)*	*Maximum (minutes)*
496.914378	*0.590578*	*365.180000*	*730.860000*

Dental technician's working time. The dental technician's working time is also an important factor and monitored in the simulation. Based on the simulation result, the average dental technician's working time is around 5.2 hours (312.314091 minutes), which is 0.5 hours longer than the theoretical one (4.7 hours).

Table 35, the result of dental technician' working time

Average (minutes)	*95% Half Length*	*Minimum (minutes)*	*Maximum (minutes)*
312.314091	*0.881527*	*146.550000*	*846.130000*

Additional performance indicators:

Total waiting time. All patients are expected to stay in a waiting list for several weeks before treatment (first intake). The waiting time that a patient waits for treatment is monitored here. The simulated total waiting time is around 94.9803 days (136771.637492 minutes), which is 0.3 days longer than the theoretical 94.6944 days (136359.9731 min).

Table 36, the result of total waiting time

Average (minutes)	*95% Half Length*	*Minimum (minutes)*	*Maximum (minutes)*
136771.637492	*555.404135*	*34025.360000*	*340358.960000*

Throughput time of the appointment day. The total throughput time of the appointment day is the same as the dentist working time. Therefore, we do not have extra results in this case.

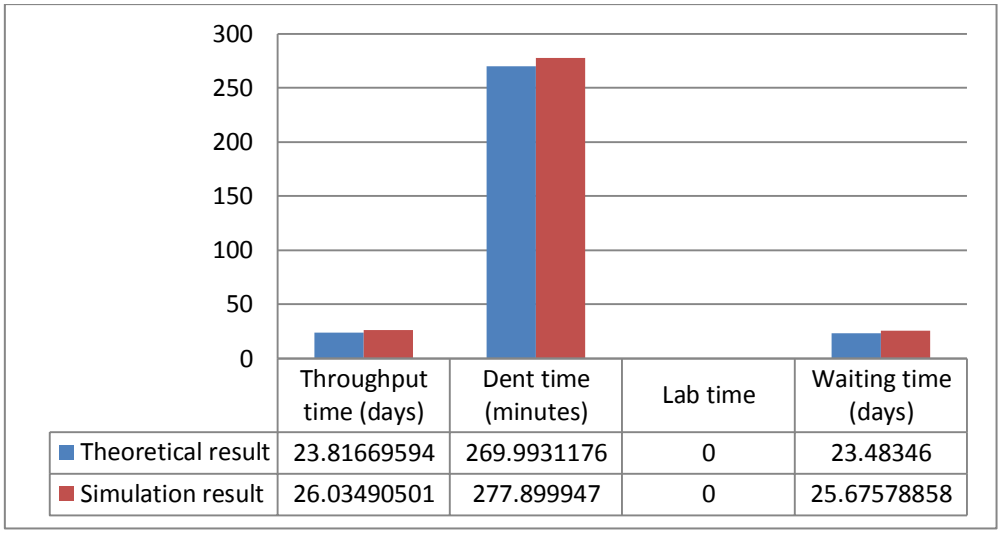
Execution time of X-ray, 3D photo and discuss treatment plan. As indicated before, this simulated result is used to give a fair comparison in the evaluation.

Table 37, the result of execution time for making X-ray and 3Dphoto and discuss treatment plan

Average (minutes)	*95% Half Length*	*Minimum (minutes)*	*Maximum (minutes)*
56.852313	*0.053473*	*50.150000*	*74.130000*

5.5 Validation of the simulation result

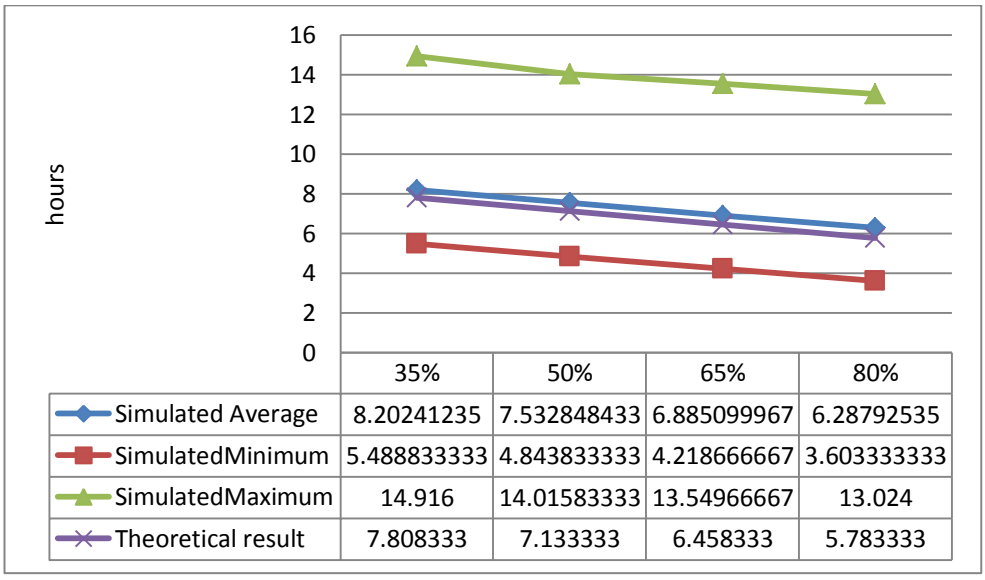
Here based on the theoretical result and the simulation result, the validity will be first checked and then we will check whether the models (OST and DMS) are reasonable or not.



	Throughput time (days)	Dent time (minutes)	Lab time	Waiting time (days)
Theoretical result	23.81669594	269.9931176	0	23.48346
Simulation result	26.03490501	277.899947	0	25.67578858

Figure 42, Theoretical result VS Simulation result (OST)

Figure 42 shows the results of comparisons between theoretical results and simulation results for total throughput time, dentist working time, dental lab working time and total waiting time. For each item, the left column stands for the theoretical result and the right one represents the simulation results. For the chart, we can see that all the theoretical results are smaller than the simulation results, but the difference is quite small, which means the simulation results in line with the theoretical results. In other words, it can be concluded that the simulation results are reasonable.

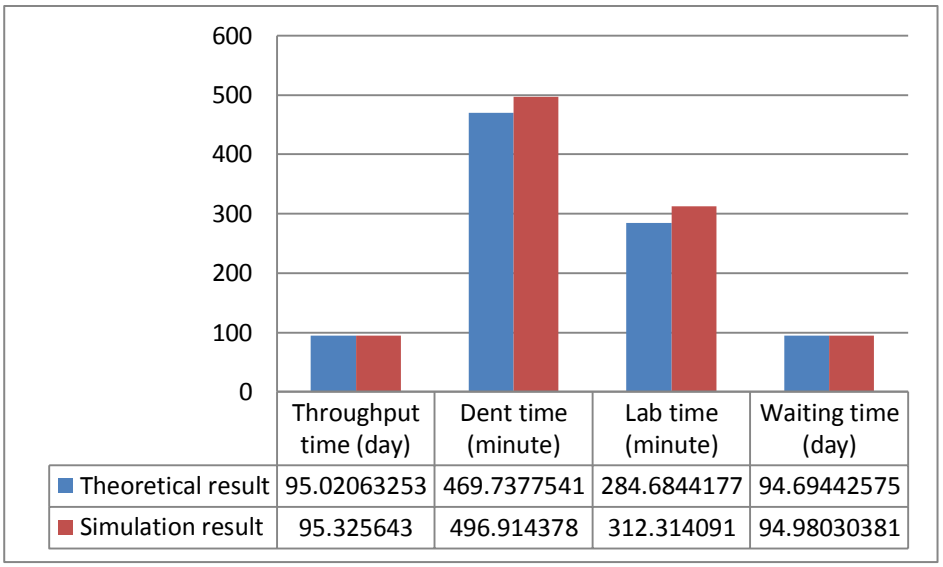


	35%	50%	65%	80%
Simulated Average	8.20241235	7.532848433	6.885099967	6.28792535
SimulatedMinimum	5.488833333	4.843833333	4.218666667	3.603333333
SimulatedMaximum	14.916	14.01583333	13.54966667	13.024
Theoretical result	7.808333	7.133333	6.458333	5.783333

Figure 43, Theoretical result VS Simulation result of appointment time with different time reduction (OST)

As seen in figure 43, all the simulated result of the appointment are almost in line with the expected value. The maximum difference between the simulation value and theoretical value is less than 8%, which is regarded as reasonable difference. All the original expectation for the total appointment time with different time reduction are smaller than 8 hours (working hours per day), however, the simulation results for the 35% time reduction is 12 minutes above daily working hours. For other level of time reduction, all the simulation result are smaller than 8 hours. In terms of the maximum value of

the appointment time, it is not very ideal. Even for the 80% time reduction on 3D printing, the maximum appointment time could still exceed 13 hours. Hence, in order to achieve the expectation that in all situation the appointment could be done by one day, the further improvements for other tasks, especially digital tasks, are very necessary.



	Throughput time (day)	Dent time (minute)	Lab time (minute)	Waiting time (day)
Theoretical result	95.02063253	469.7377541	284.6844177	94.69442575
Simulation result	95.325643	496.914378	312.314091	94.98030381

Figure 44, Theoretical result VS Simulation result (DMS)

Similarly, figure 44 indicates the comparisons between theoretical results and simulation results for total throughput time, dentist working time, dental lab working time and total waiting time in DMS. As showed from the chart, we can see that there is reasonable difference between the theoretical result and simulation result, which indicate that the simulation results are reliable.

5.6 Summary

The main purpose for this chapter is to set up simulation models and achieve the quantitative results of TO-BE TO-BE model. For better understanding and analysing the model, several assumptions regarding different aspects are made in the first place. Six aspects are taken into account, which are time, patients, dentist, dental lab technician, process and execution of task. As the simulation models are set up based on these assumptions, each assumption is cleared explained in detailed or presented by figures; For example, the time structure of the model is displayed in order to understand the assumptions on time. After that, the performance indicators will be given. We consider 5 performance indicators. Except the 3 indicators that indicated in ITI project (the throughput time of the entire process, the time needed by the dentists and the timed needed by the dental lab technicians), there are two additional performance indicators are introduced in this case which are the total waiting time and the total dental appointment time. Finally, the experiment result of performance indicators for crown treatment and prosthesis treatment will be presented separately. The average time, confident interval, maximum value and minimum value of each indicator are shown in the table. In order to obtain a better view of the simulated results, the briefly quantitative comparison with theoretical results is also given. Based on the comparisons, the validation of the simulation for two models are proved. Furthermore, the simulation result is acceptable, except the maximum appointment hours for the treatment, which exceed the total working time per day. Therefore, an further improvement on other tasks in OST is necessary to reach the aim of one day stop in all cases. According to the simple comparisons, we conclude that most of the simulated results are reliable.

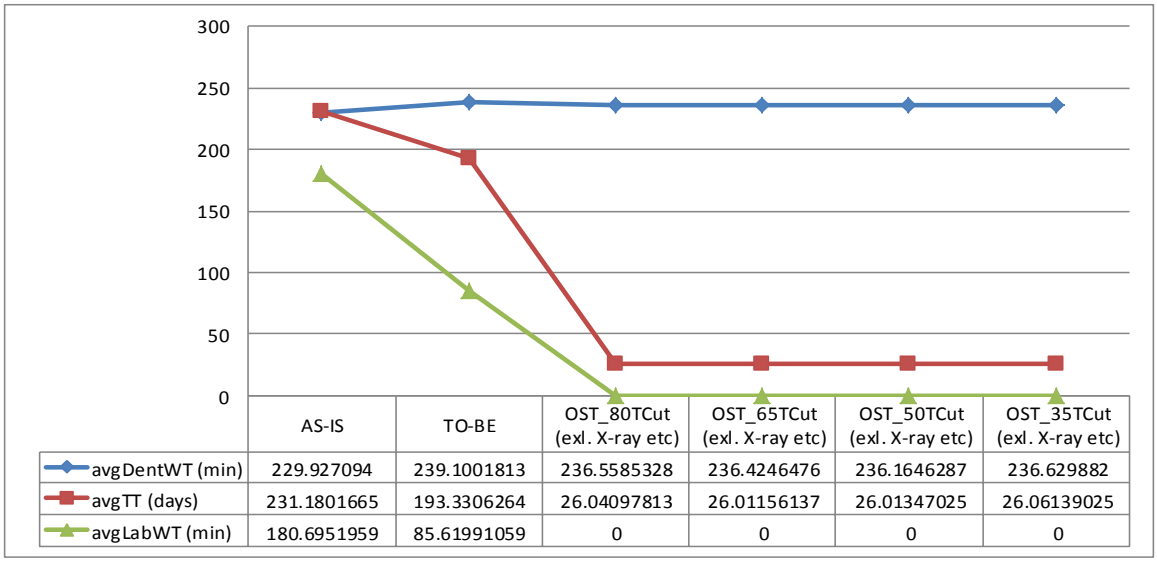
Chapter 6

6. Evaluation

A validation on the simulation result is already been done in chapter 5, where we obtained some qualitative results on the performance indicators. In this chapter, we will give an in-depth analysis and quantitative comparisons between TO-BE TO-BE models and all previous models.

6.1 Comparison of Crown treatment

The main purpose of this section is to make comparison between three simulated models of crown treatment and discuss if the redesigned model is better than previous one. The data sources for this comparison are from the simulated results of AS-IS model, TO-BE model and TO-BE TO-BE model(OST).



	AS-IS	TO-BE	OST_80TCut (exl. X-ray etc)	OST_65TCut (exl. X-ray etc)	OST_50TCut (exl. X-ray etc)	OST_35TCut (exl. X-ray etc)
avgDentWT (min)	229.927094	239.1001813	236.5585328	236.4246476	236.1646287	236.629882
avgTT (days)	231.1801665	193.3306264	26.04097813	26.01156137	26.01347025	26.06139025
avgLabWT (min)	180.6951959	85.61991059	0	0	0	0

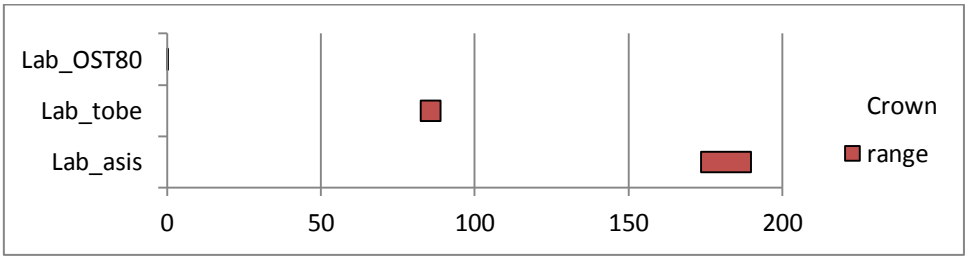
T-TEST	AS-IS<-> OST_80TimeCut		TO-BE <-> OST_80TimeCut		OST_80TimeCut <-> OST_65TimeCut		OST_65TimeCut <-> OST_50TimeCut		OST_50TimeCut <-> OST_35TimeCut	
	t-value	p-value	t-value	p-value	t-value	p-value	t-value	p-value	t-value	p-value
avgDentWT (min)	-9.88	0.00*	3.59	0.40	0.27	0.79	0.50	0.62	-0.87	0.39
avgTT (days)	377.02	0.00*	334.34	0.00*	0.28	0.78	-0.17	0.99	-0.43	0.67
avgLabWT (min)	646.80	0.00*	580.91	0.00*	-	-	-	-	-	-

Figure 45, the comparisons of AS-IS, TO-BE, OST with different time reduction (excl. X-ray and discuss treatment plan).

There are 4 figures that used to display the differences between the simulated results from three different models. Figure 45 is a summarized figure which shows the average simulated value of dentist working time, dental lab working time and total throughput time in AS-IS model, TO-BE model and OST model with different level of time reduction respectively. Again, the dentist's working time is defined as the sum of the duration of tasks (except X-ran and discuss treatment plan) that are performed by dentist, dental lab working time is measured as the total time needed by the dental technicians to perform the tasks in the workflow and total throughput time is the duration from patient arrived in the workflow until the completion of the last task in the workflow. Note that we have two types of dentist working time, one includes the X-Ray and discuss treatment plan and the other does not, and the latter one is use to do the comparison in most of time. The reason behind that is the X-Ray and discuss treatment plan are not compulsory tasks in AS-IS and TO-BE model, hence the time of doing these two tasks are exclusive in these two models. However, these two tasks are

inclusive in OST model as we consider that X-Ray and treatment plan are able to improve the patient's satisfaction and make the treatment plan more clearer to the patients indicated by Ali Tahmaseb. As X-Ray and treatment plan are also not compulsory in OST model but we include them, it is reasonable to drop them when do the comparison.

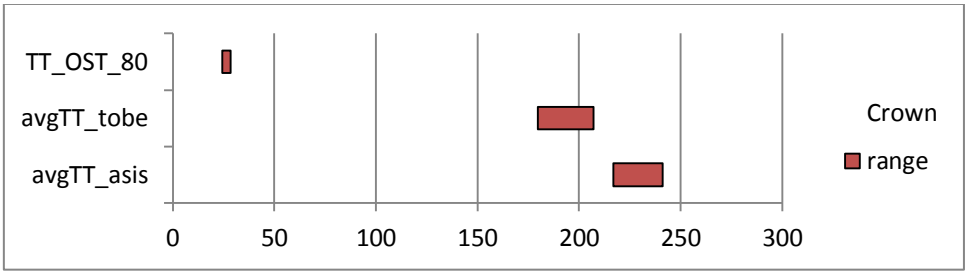
In order to give a scientific analysis, the T-test is adopted here to check whether the differences between two samples are statistically significant. The significance level (α) defined in this study is 0.05 and null hypothesis is no differences, which means if the p-value is less than the 0.05 (significance level), the null hypothesis is rejected and the result is said to be that difference is statistically significant. The general comparisons can be seen from the figure 45, the total throughput time and dental lab working time are sharply decreased when comparing with the AS-IS and TO-BE models, while the dentist working time (exclude X-ray etc.) are in between of the value of AS-IS and TO-BE models. As showed in the T-test, the differences among OST with different level of time reduction on 3D printing are ***not*** statistically significant. Therefore, only the time value of OST with 80% time reduction will be selected in the later comparison. The more detailed comparisons can be seen from other 3 figures presenting below.



T-TEST	AS-IS<-> OST_80TimeCut		TO-BE <-> OST_80TimeCut		AS-IS <-> TO-BE	
	t-value	p-value	t-value	p-value	t-value	p-value
avgLabWT (min)	646.80	0.00*	580.91	0.00*	301.00	0.00*

Figure 46, the comparisons of dental lab time

The comparison results of dental technician's working time for crown treatment are shown in figure 46. The first row of upper figure stands for the range of average value of dental technician's working time in OST, and the second and the third row represent the range of average value of dental technician's working time in TO-BE model and AS-IS model respectively. Based on the result of T-test, the differences of dental technician's working time between all three models are statistically significant. The dental technician's working time is zero in OST model, which means that the dental technician's working parts are completely eliminated in OST model. In AS-IS and TO-BE models, dental lab is responsible for most of producing tasks, such as make and design crowns and select abutments. However, due to the new digital technologies, introduction of 3D printer and designing platform, dental lab's responsibilities/tasks are all transferred to dentist's part, and this responsibility transfer make one stop treatment become realizable.

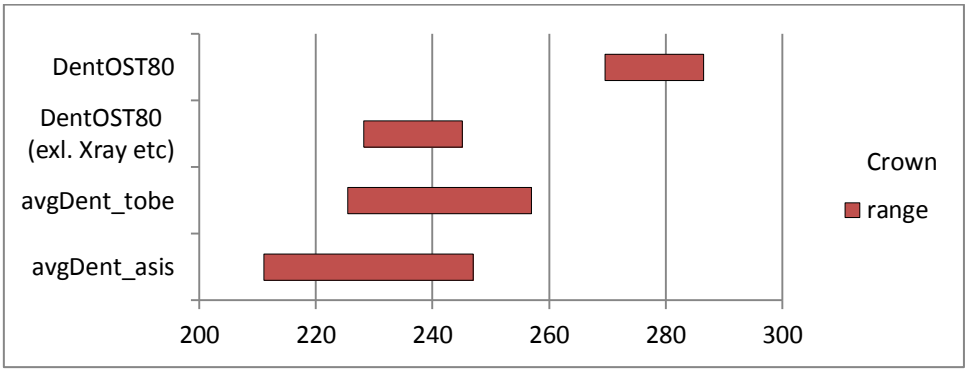


T-TEST	AS-IS<->	TO-BE <->	AS-IS <-> TO-BE

	OST_80TimeCut		OST_80TimeCut			
	t-value	p-value	t-value	p-value	t-value	p-value
avgTT (days)	377.02	0.00*	334.34	0.00*	51.70	0.00*

Figure 47, the comparisons of total throughput time

Figure 47 displays the comparisons results of total throughput time for crown treatment. Similarly, 3 different rows from upper figure stand for the simulated results in 3 different models respectively. With the result in T-test, we could conclude that the differences of dental technician's working time between all three models are statistically significant as well. Therefore, with this in mind, we could analyse the differences as indicated in the figure. There is an obvious decrease of total throughput time in OST. As the name of OST, all the tasks are arranged within one day which can sharply reduce the duration of the total treatment procedure. In the AS-IS and TO-BE models, dental lab is indispensable parts for complete the whole treatment, which means that more time has to give to the transportation between dentist's office and dental lab and queuing for dental technicians to finish the designing and producing, correspondingly, there are more time gaps between each appointment since the dentist has to wait for the response of dental lab to adjust their treatment plan. However, when the dental lab is completed replaced by new technologies and all their responsibilities are given to the dentist in OST model, the total throughput time is reduced significantly.



T-TEST	AS-IS<-> OST_80TimeCut		TO-BE <-> OST_80TimeCut		OST_80TimeCut <-> OST_80TimeCut(noX.D.)		AS-IS <-> TO-BE	
	t-value	p-value	t-value	p-value	t-value	p-value	t-value	p-value
avgDentWT (min)	-9.88	0.00*	3.59	0.40	84.34	0.00*	-10.88	0.00*

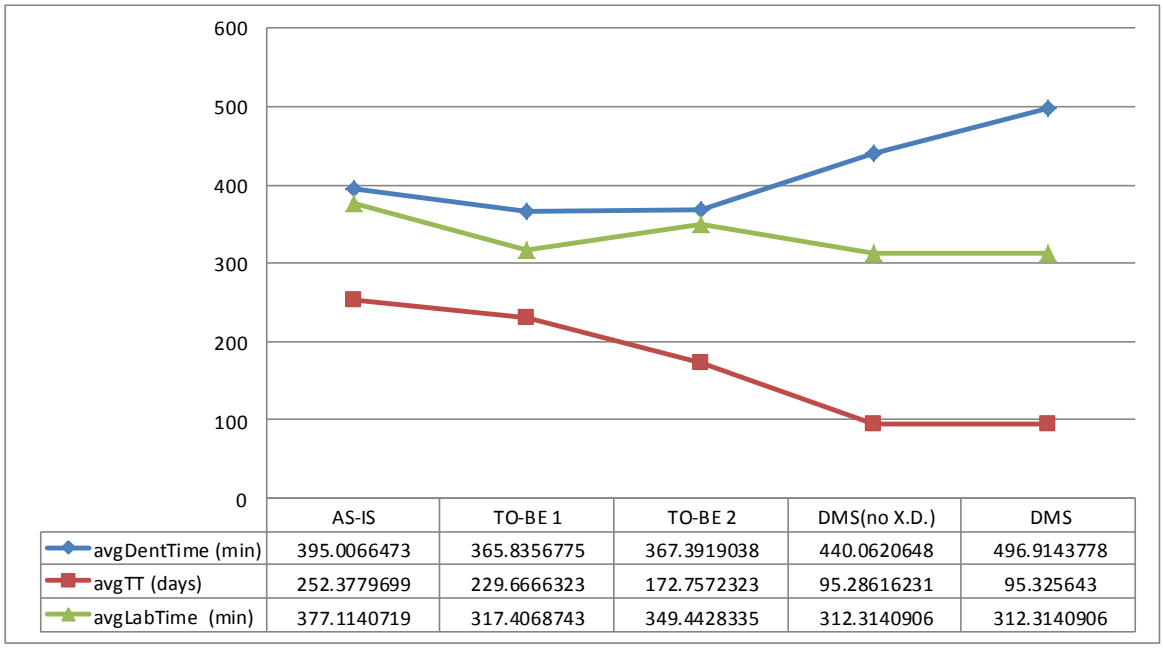
Figure 48, the comparisons of dentist's working time

The last figure (figure 48) indicated the comparison results of dentist's working time for crown treatment. The first row in the upper figure represents the range of average value of dentist's working time in OST with 80% time reduction and the second row stands for the value after deducting the time of making X-Ray and treatment plan. The third and the fourth row indicated the same type value in TO-BE and AS-IS model. As indicated above, the second row will be used as the relevant value to do the comparison. On one hand, the figure shows that the range of the dentist's working time in OST is lied within the range of that in TO-BE and AS-IS model, and according to the T-test, p-value is larger than 0.05, which means that there is no significantly differences between OST and TO-BE model. On the other hand, the differences between OST and AS-IS is statistically significant and in average dentist's working time in OTS is around 6 minutes longer than AS-IS. The reason is that all the tasks of dental lab in the AS-IS and TO-BE model are assigned to dentist in OST. Although the introduced new technology is more efficient, the total dentist's working time is not able to reduce in a very big extent. Seen from another way, even the time is not improved in a very big extent, the dentists complete more tasks using the same time with TO-BE situation, which means the dentist's working efficiency is highly improved in OST.

To sum up, there are several obvious improvements on both dental technician's side and patient's side. Due to the new technologies, the dentist's working time in OST is in line with the time in TO-BE and has only a limited increase compare to AS-IS, but the whole treatment process could be finished within one appointment day without the involvement of other parties which means the efficiency of dentist is highly enhanced. In general, it can be concluded that the OST model is given a positive result.

6.2 Comparison of Prosthesis treatment

The main objective of this section is to make comparison between four simulated models of prosthesis treatment and discuss if the redesigned model is better than previous ones. The data sources for this comparison are from the simulated results of AS-IS model, TO-BE 1 model (where an Intra-Oral Scan of the teeth is made, the final crown is made using CAD/CAM techniques and etc.), TO-BE 2 model (three mini implants are placed, the implants are placed using guided surgery, the final prosthesis is made using CAD/CAM techniques and etc.), and TO-BE TO-BE model (DMS).

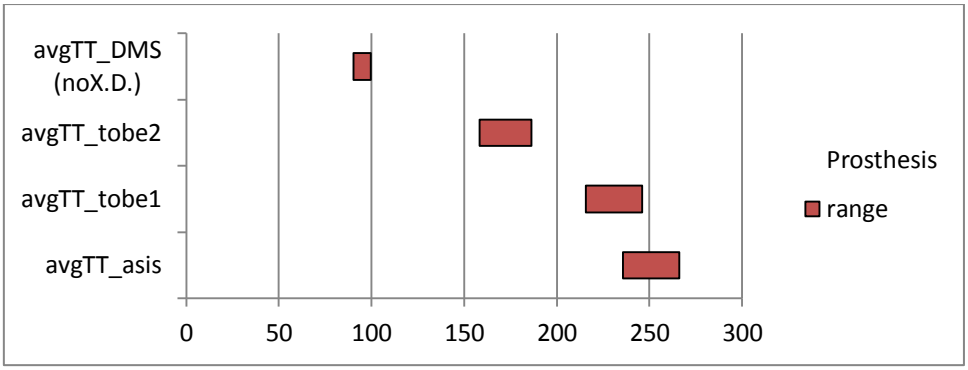


	AS-IS	TO-BE 1	TO-BE 2	DMS(no X.D.)	DMS
avgDentTime (min)	395.0066473	365.8356775	367.3919038	440.0620648	496.9143778
avgTT (days)	252.3779699	229.6666323	172.7572323	95.28616231	95.325643
avgLabTime (min)	377.1140719	317.4068743	349.4428335	312.3140906	312.3140906

T-TEST	AS-IS <-> DMS(noX.D.)		TO-BE 1 <-> DMS(noX.D.)		TO-BE 2 <-> DMS(noX.D.)		DMS <-> DMS(noX.D.)	
	t-value	p-value	t-value	p-value	t-value	p-value	t-value	p-value
avgDenttime (min)	-64.94	0.00*	-118.65	0.00*	-204.22	0.00*	135.60	0.00*
avgTTtime (days)	240.15	0.00*	193.88	0.00*	144.12	0.00*	0.14	0.89
avgLabtime (min)	84.51	0.00*	7.97	0.00*	60.12	0.00*	-	-

Figure 49, Results for the experiments of AS-IS, TO-BE1, TO-BE 2 and DMS

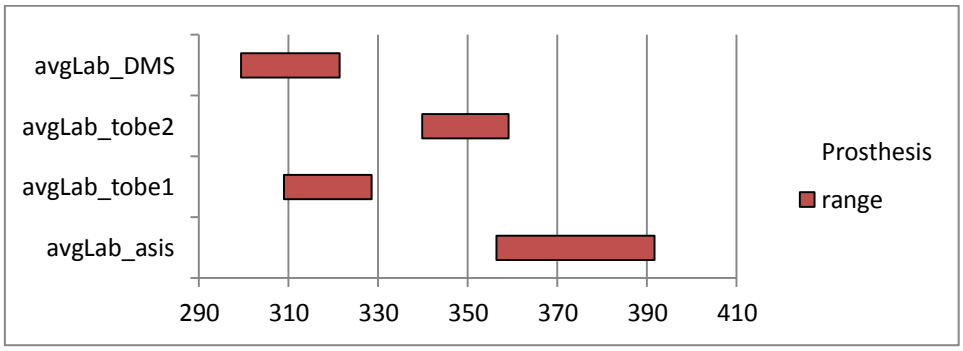
The figure 49 is a summarized figure, and the main function of this figure is to give a clear comparison results between the simulated results of dentist's working time, total throughput time and dental technician's working time in AS-IS, TO-BE 1, TO-BE 2 and DMS model, respectively. Meanwhile, a T-test is presented to indicate the significant differences between different models. In general, the total throughput time in DMS model is sharply decreased, the dental technician's working time has limited decrease on TO-BE 1 and an obvious improvement on TO-BE 2 and AS-IS model. However, the dentist working time is significantly increased. Furthermore, only the differences between the throughput time and lab time of DMS and of DMS without X-ray and treatment plan are ***not*** statistically significant, all the rest pairs showed in T-test are significant different.



T-TEST	AS-IS <-> DMS(noX.D.)		TO-BE 1 <-> DMS(noX.D.)		TO-BE 2 <-> DMS(noX.D.)	
	t-value	p-value	t-value	p-value	t-value	p-value
avgTTtime (days)	240.15	0.00*	193.88	0.00*	144.12	0.00*

Figure 50, the comparisons of total throughput time

The comparison result of the total throughput time between these four models is shown in figure 50. The first row of the upper figure represents the simulation results of total throughput time without making X-ray and treatment plan in DMS, while other three rows strand for the simulation results in previous models. From T-test, we can conclude that the differences between DMS and previous three models are all statistically significant. From the figure, we can see that there is a sharply decrease in the total throughput time from AS-IS/TO-BE 1/TO-BE 2 model to the DMS model. One of the main reason leading to this positive result is re-organization of each appointment. In DMS model, the dental workflow is re-organized in order to reduce the time efforts of the whole treatment procedure, such as appointments that used to be in different days are re-arranged into the same day result in the decrease in waiting time.

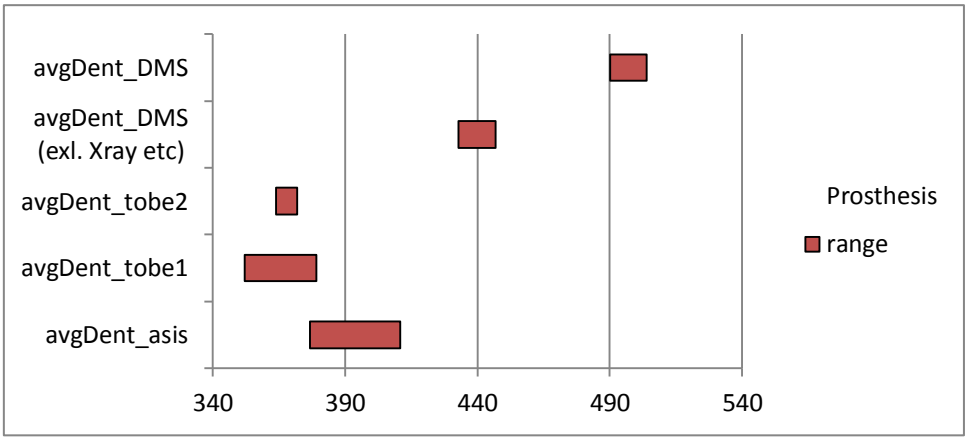


T-TEST	AS-IS <-> DMS		TO-BE 1 <-> DMS		TO-BE 2 <-> DMS	
	t-value	p-value	t-value	p-value	t-value	p-value
avgLabtime (min)	84.51	0.00*	7.97	0.00*	60.12	0.00*

Figure 51, the comparisons of average dental lab time

Figure 51 indicates the comparison results of the dental technician's working time. Similarly, each row represents simulated results of dental technician's working time in DMS, AS-IS, TO-BE 1 and TO-BE 2, respectively. As shown in T-test, the differences of AS-ISvsDMS, TO-BEvsDMS and TO-BE2vsDMS are all statistically significant. As seen from the figure, the total dental lab working time is obvious declined when comparing to the previous models. To be specific, the main reason why dental lab working time in DMS is smaller than in TO-BE 2 is that the producing of physical impression and physical registration bite are replaced by the digital work of IOS and CT scan. When comparing to TO-BE 1 model, the time reduction is mainly caused by using the 3 mini-implant, where the healing time for osseointegration falls outside the workflow as the implants are placed in the last

step. Furthermore, in DMS model, the integration of IOS and mini-implants, which are the two technologies in TO-BE 1 and TO-BE 2 respectively, lead to a very obvious time decrease when comparing to AS-IS model.



T-TEST	AS-IS <-> DMS(noX.D.)		TO-BE 1 <-> DMS(noX.D.)		TO-BE 2 <-> DMS(noX.D.)		DMS(noX.D.) <-> DMS	
	t-value	p-value	t-value	p-value	t-value	p-value	t-value	p-value
avgDenttime (min)	-64.94	0.00*	-118.65	0.00*	-204.22	0.00*	135.60	0.00*

Figure 52, the comparisons of dentist's working time

The comparison results of dentist's working time is displayed in figure 52. Same as the comparisons in crown treatment, the dentist's working time that will used to do the comparison is deducted by the total time of making X-ray and treatment plan and named as *avgDent_DMS (exl. Xray etc)* in the first row of the upper figure. We make this adjustments for the same purpose as that in comparison of crown treatment. However, based on the T-test, the differences between DMS and all previous models are statistically significant and the total dentist's working time is still longer than that in previous models. The reason behind the result is that digital works such as IOS are very time-consuming task in current state comparing to the physical impression. Besides, it is taken for two times during the whole dental procedure. We expect that the efficiencies of these two tasks will be increased in near future and total time spent on digital tasks will be reduced.

6.3 Summary

The main target of this chapter is to analyse the simulation result of the OST and DMS. First of all, a comparisons between all the previous models and OST is explained and analysed. Basically, the overall result is positive. Especially, the dental technician's work is totally eliminated. Total throughput time is also greatly decreased. Only the dentist's working is remained the same with TO-BE situation and several minutes longer than AS-IS situation, which is because the new technology is still very time consuming. Secondly, the same comparisons are made for DMS. Both throughput time and dental technician's working time are declined sharply, but there is an increase on dentist's working time which is mainly caused by the work of extra IOS. Therefore, the result indicate that there is still an need for further improvement on the digital work to reduce the dentist's working time.

Chapter 7

7. Conclusions

As indicated in section 1.2, all the problems and corresponding research goals are delivered at the beginning of the project. At this point, the final summary from this project will be presented based on the goals. Furthermore, we will also present some ideas on the future work of the TO-BE TO-BE dental workflow.

7.1 Summary

In this thesis we studied the conventional dental value chain (AS-IS situation) and the redesigned dental workflow in ITI project (TO-BE situation), where we realized seven research problems. Based on those problems, one research goal and seven sub research goals are derived, in order to develop the TO-BE TO-BE dental workflows on aspect of crown treatment and prosthesis treatment by means of digitalization. To accomplish the aim of project, seven sub goals are satisfied as following.

- ***Sub research goal 1****: Describe and understand the AS-IS, TO-BE situation and the technique improvement in between.*

In preliminary part (chapter 2), we first described the five-phase procedure of the conventional crown and prosthesis replacement, in order to obtain an overview of conventional dental workflows. Being aware of the overall dental workflows, we were able to understand and analyse the improvement of dental process in ITI project. Thus, the simplified AS-IS and TO-BE models of the crown and prosthesis treatment are described and the main modifications between the AS-IS and TO-BE are presented as well. With these information, the sub research goal 1 is satisfied.

- ***Sub research goal 2****: Structure the steps for developing the redesigned future workflows and using the devil's quadrangle to select key indicators for evaluation.*

In research methodology, we proposed a four-steps procedure to develop the TO-BE TO-BE dental workflow. Especially, two phases, the redesign phase and the validation phase, are introduced as the key approaches for the development of the TO-BE TO-BE dental workflow. Repeating these two phases, an redesigned dental workflow will be validated and selected for the further modelling and simulation. Furthermore, the modelling language, data sources and evaluation method are all determined here.

- ***Sub research goal 3****: Developing the interesting workflows that will become valid in the later future (TO-BE TO-BE situation) and identify it by interviews with dental professionals.*
- ***Sub research goal 4****: Describe the differences of the model and give a theoretical analysis on aspect of key indicators.*

The one stop treatment (OST) for crown placement and the digital mini-implants solution (DMS) for prosthesis placement are described in the chapter of process model. To better understand the digitalization of dental workflow, we also explained the digital workflow of the redesigned TO-BE TO-BE process. Besides, the main modifications from the original model to the TO-BE TO-BE model are analysed by redesign heuristics to present benefits and drawbacks on it. In the end, the theoretical analysis is used for further improvement of the model.

- ***Sub research goal 5**: Quantify impacts of selected future workflows by means of simulation using CPN tool.*

To model the process in the CPN tool, the basic setup and assumptions should be first defined and declared. In simulation experiment, each assumption is cleared explained in details or presented by figures. Meanwhile, the quantitative result of the performance indicators on aspect of average value, confident interval, maximum value and minimum value are shown in the table.

- ***Sub research goal 6**: Evaluate the main difference between the AS-IS, TO-BE and TO-BE TO-BE model.*

The simulation result of OST and DMS are presented in the chapter 6. First of all, the experiment results are proved to be validated, based on the comparisons of the theoretical result and simulation result. All the simulation results are acceptable, except the appointment hours for OST, which exceed the limitation of 8 hours (working hours per day). Thus, without further time reductions on the tasks of OST, it will not reach the aim of one stop treatment.

- ***Sub research goal 7**: Evaluate the major benefits of the redesigned future workflows for dentist with aspect of all key indicators.*

In OST, the total working time for dentist (exl. Xray etc) is almost the same with it in AS-IS and TO-BE situation. However, except the conventional work, dentist also completed the designing and production of the drilling guide, crown and abutment. We could conclude that within the same time duration the efficiency of dentist is greatly improved. In addition, all the treatment are done by one dentist, which minimizing the human errors happened during the communication between dentists and dental lab. Therefore, the quality of the treatment is enhanced as well.

In terms of DMS, the dentist's working time is increased comparing to the previous situation. The main reason is that many digital jobs are assigned to dentist and those jobs are very time consuming such as IOS, 3D photo, integration of digital works and etc. However, with the fast pace in the development of digital technology, we believe that in the next 5 to 10 years the execution time for the digital work will be greatly reduced. Therefore, at that time, the DMS could bring great benefit for the dentist.

7.2 Future works

With this study, it was possible to demonstrate that the TO-BE TO-BE dental workflow can be more effective than a AS-IS or a TO-BE dental workflow on aspect of the time dimension. However, with the limitation of the data resources, the improvement on aspect of cost is not proved yet. A further study with the relative information on cost is necessary to obtain an overall picture of the TO-BE TO-BE dental workflow.

Meanwhile, conclusions are based on the analysis performed using a simulation model and it is only a simplification of the real situation. In this case, it is important to propose a clinical testing for the TO-BE TO-BE dental workflow to further prove the reliability.

Furthermore, in our TO-BE TO-BE situation, the 3D printer is only useful for producing the drilling guide, crown and abutment. In the far future, we believe that the biocompatible materials for the 3D printer will be developed for producing the implants. At that time, it will bring the great flexibility for the onsite production and improvement in the whole process.

Bibliography

[1] H. A. Reijers and S. L. Mansar, "Best practices in business process redesign: an overview and qualitative evaluation of successful redesign heuristics." ELSEVIER, 23-Apr-2004.

[2] "Surgical tooth extractions: Creating a gum tissue flap." [Online]. Available: http://www.animated-teeth.com/tooth_extractions/a-gum-tissue-flaps.htm. [Accessed: 10-Aug-2012].

[3] "How are dental implants placed?" [Online]. Available: http://www.osseo.org/NEWhowAreImplantsPlaced.html. [Accessed: 10-Aug-2012].

[4] P. I. Brånemark, "Osseointegration and its experimental background," *J Prosthet Dent*, vol. 50, no. 3, pp. 399–410, Sep. 1983.

[5] "Placing Dental Implant Abutments - Understanding Dental ImplantsUnderstanding Dental Implants." [Online]. Available: http://dentalimplantsunderstand.info/dental-implant-abutments/. [Accessed: 11-Jul-2012].

[6] "The dental crown procedure: What steps are involved when a crown is made for a tooth?" [Online]. Available: http://www.animated-teeth.com/dental_crowns/t4_dental_crowns_steps.htm. [Accessed: 10-Aug-2012].

[7] "Procedure For Crown Placement, Treatment For Crown Placement, Temporary Dental Crown Procedure | identalhub.com." [Online]. Available: http://www.identalhub.com/article_procedure-for-crown-placement-270.aspx. [Accessed: 19-Jul-2012].

[8] "Cyrtina » PRIMERO Intra-Oral Scan Service » Cyrtina." [Online]. Available: http://www.cyrtina.nl/cyrtina-labs/cyrtina-ios-scan-service/. [Accessed: 15-Jul-2012].

[9] "CPN Tools Homepage." [Online]. Available: http://cpntools.org/. [Accessed: 15-Aug-2012].

[10] W. M. P. Aalst, "Business Process Management Demystified: A Tutorial on Models, Systems and Standards for Workflow Management," in *Lectures on Concurrency and Petri Nets*, vol. 3098, J. Desel, W. Reisig, and G. Rozenberg, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2004, pp. 1–65.

[11] W. M. P. Aalst, "Three Good Reasons for Using A Petri-Net-Based Workflow Management System," in *Information and Process Integration in Enterprises*, vol. 428, T. Wakayama, S. Kannapan, C. M. Khoong, S. Navathe, and J. Yates, Eds. Boston, MA: Springer US, 1998, pp. 161–182.

[12] "Home." [Online]. Available: http://www.tandartsenpraktijkwilhelminaweg.nl/. [Accessed: 06-Aug-2012].

[13] "Academisch Centrum Tandheelkunde Amsterdam." [Online]. Available: http://www.acta.nl/nl/index.asp. [Accessed: 06-Aug-2012].

[14] "Welkom." [Online]. Available: http://www.ttlzutphen.nl/. [Accessed: 06-Aug-2012].

[15] "Dental Wings." [Online]. Available: http://www.dental-wings.com/. [Accessed: 06-Aug-2012].

[16] Schonenberg, Mans, R.S., M.H., Rusell, N.C., Mulyar, N.A. and Aalst van der, W., "Towards a taxonomy of process flexibility," *Proceedings of CAiSE'08 Forum*, 2008.

[17] "Dental hygienist - Wikipedia, the free encyclopedia." [Online]. Available: http://en.wikipedia.org/wiki/Dental_hygienist. [Accessed: 15-Aug-2012].

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Appendices

A Abbreviations and definitions

AS-IS situation	It is the current conventional dental workflow where the traditional measurement is used
TO-BE situation	New technique is properly used in this situation, such as intra oral scan.
TO-BE TO-BE situation	The future process will be developed in this situation.
BPM	Business Process Management is a systematic approach to improving an organization's business processes. BPM activities seek to make business processes more effective, more efficient, and more capable of adapting to an ever-changing environment.
Business Process Modeling	The act of creating a model of a business process and results in a structural representation, description or diagram, which defines a specified flow of activities. Can also refer to Business Process Management.
OST	One stop treatment
DMS	Digital mini-implants solution
ITI	International Team of Implantology project
ACTA	Academisch Centrum Tandheelkunde Amsterdam. The ACTA is a collaborative venture involving the Faculties of Dentistry at the University of Amsterdam and VU University Amsterdam. In the department of Oral Implantology and Prosthodontics experienced implantologists are working as well as dentists that are educated in order to become an implantologist. For all patients that are treated, in the clinic management system, all the appointments and their timing are stored.
CPN	In short of colored Petri nets.
CPN tools	CPN Tools is a high level Petri net tool. It supports the basic Petri nets plus timed Petri nets and Colored Petri nets. It has a simulator and a state space analysis tool is included. CPN Tools is originally developed by the CPN Group at Aarhus University from 2000 to 2010. The main architects behind the tool are Kurt Jensen, Soren Christensen, Lars M. Kristensen, and Michael Westergaard. From the autumn of 2010, CPN Tools is transferred to the AIS group, Eindhoven University of Technology, The Netherlands. CPN Tools comprises two main components, a graphical editor and a backend simulator component. The graphical editor is written in the academic language, BETA, and the simulator backend is written in the Standard ML variant SML/NJ.

B Selection of the most promising model

In order to make a deliberate choice to select the most promising TO-BE TO-BE model in the validation phase, the impacts on time, cost, quality and flexibility of all the other developed TO-BE TO-BE models are evaluated as well. All the modifications and evaluation result will be explained here.

B.1 modifications for each TO-BE TO-BE models (Crown treatment)

For crown treatment, the AS-IS model is selected as the benchmark, since all the models are developed originally from it. The overview of all the modifications for each TO-BE TO-BE model are presented as below.

Table 38, overview of all the modifications for each TO-BE TO-BE model (crown treatment)

Redesign heuristics	*AS-IS vs OST*	*AS-IS vs TO-BE TO-BE 1*	*AS-IS vs TO-BE TO-BE 2*
Resequence the task:	D: Discuss treatment plan	D: place implant	D: place implant
	D: place implant		D: IOS and CT-scan
Task elimination:	D: check-up	D: check-up	D: check-up
	D/H: hygiene	D/H: hygiene	D/H: hygiene
	D: expose implants	D: expose implants	D: expose implants
	L: make individual impression trays	L: make individual impression trays	L: make individual impression trays
	D: make impressions	D: make impressions	D: make impressions
	D: checklist and study model		
Addition of task:	D: design drilling guide	L: make drilling guide	L: make drilling guide
Integral technology	D: make X-ray	D: IOS and CT-scan	D: IOS and CT-scan
	D: IOS and CT-scan		
	D: 3D printing		
Task automation	D: process IOS and CT-scan	D: process IOS and CT-scan	D: process IOS and CT-scan
Resource centralization	D: Design crown and abutment		

Since all the modifications for OST are already explained and evaluated in chapter 4, here we are only going to explain and evaluate the modifications that are not mentioned in chapter 4. After that, the overall impact of these TO-BE TO-BE models will be given.

Seen from the table above, for each redesign heuristic, the number of modifications in TO-BE TO-BE 1 are less than in DMS. Especially, a majority of modifications are included in DMS, except the addition of task, L: make drilling guide and actually this is the only task that is not discussed before. Here the explanation and evaluation for this task are given as following.

Addition of task: make drilling guide

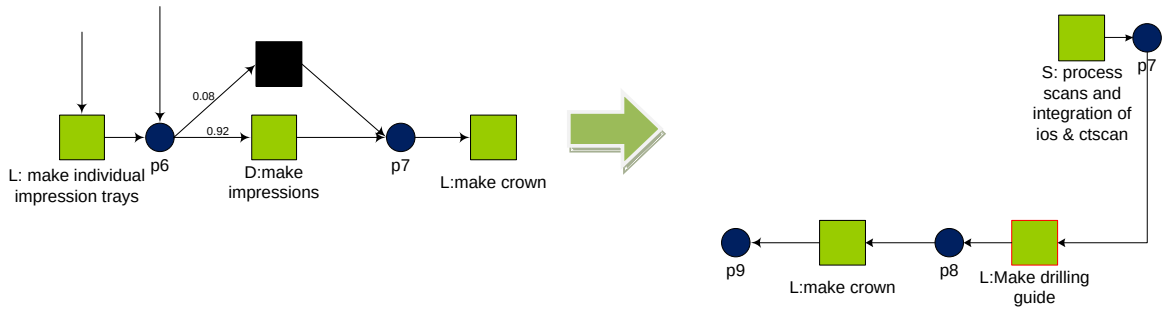


Figure 53, Addition of task: make drilling guide

As indicated before, drilling guide is a very crucial tool for the implants surgery. With the help of drilling guide, it is unnecessary to raise the gum flap for exposing the jaw bone before the implants placement, then the healing phase can be eliminated, and the unique surgery can be completed within one appointment. Making drilling guide can be executed right after when dental technician received the result of processing scans. And in the dental lab, some dental technicians are professionals for designing and produce the drilling guide. Therefore, both the designing and producing of the drilling guide will be done within this task.

Table 39, impact of Addition of task: make drilling guide

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Addition of task: make drilling guide	Time	-	Drilling guide was already applied in the prosthesis treatment, therefore we could obtain the timing information there. The total time is following a uniform distribution and range from 4.8 days to 6.4 days.
	Cost	- -	Cost addition on resource of dental technician and producing materials.
	Quality	+	The designing of the drilling guide will be finished on the designing software and the producing can be done by milling machine, thus it can be regarded as an partial digitalized and automatic task.
	Flexibility	+	Making drilling guide can be finished by dental technician and milling centre.

Therefore the overall impact of TO-BE TO-BE 1 can be described as below.

Table 40, overall impact on time, cost and quality of all the modifications for TO-BE TO-BE 1 (crown)

Number	*Name of the modification*	*Time*	*Cost*	*Quality*	*Flexibility*
1	*Elimination of the task: check-up*	*0*	+	*0*	*0*
2	*Elimination of the task: D/H:hygiene*	*0*	+	*0*	-
3	*Elimination of the task: Expose implant*	+	+	*0*	*0*
4	*Elimination of the task: make individual impression trays*	+ +	+ +	*0*	*0*
5	*Elimination of the task: make impressions*	*0*	+ +	*0*	*0*
6	*Addition of task: make drilling guide*	-	- -	+	+
7	*Integral technology: IOS and CT-scan*	-	- -	+	+
8	*Task automation: Process IOS and CT scan*	*0*	-	+ +	+ +
9	*Resequencing the task: place implant*	*0*	*0*	*0*	*0*
	Overall impact caused by the modifications	*1 plus positive*	*2 plus positive*	*4 plus Strong positive*	*3 plus positive*

Note that in terms of the time of "Integral technology: IOS and CT-scan", in OST the waiting time of this additional task is zero because of the one day treatment, however in this case the waiting time is still remained. It is around 15 days based on the timing information from TO-BE model. Thus, the impact on the dimension of time is different with OST, it is 1 minus negative in this case. The same reason is also applied in TO-BE TO-BE 2.

In terms of the evaluation result, shown as the table above, TO-BE TO-BE 1 model have positive impact on all the four dimensions. Especially on the quality, it has a strong improvement.

When it comes to TO-BE TO-BE 2, the modification that we do not mentioned is the resequence of task making IOS and CT-scan.

Resequence the task: D: IOS and CT-scan

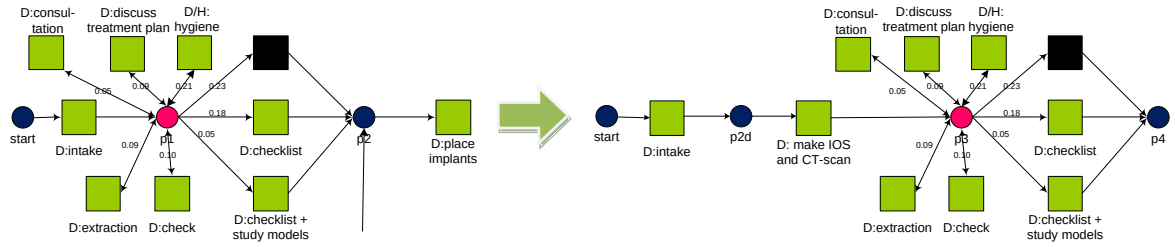


Figure 54, Resequence the task: D: IOS and CT-scan

This is the different part between TO-BE TO-BE 1 and TO-BE TO-BE 2. The reason to resequence IOS and CT-scan is to eliminate one appointment of it. In TO-BE TO-BE 1, there are at least four appointments which are appointment for intake as first one, for optional tasks and medical checking as second one, for digital impression and CT-scan as third one and for final placement of implant and crown as the final one. In TO-BE TO-BE 2, immediately after the intake, patient will receive the IOS and CT-scan which can be used in the medical checking as well. After that, a certain number of medical checking will be given to examine the availability of patient for treatment in second appointment. If all the checks are positive, then the IOS and CT-scan will be processed and send to the dental lab for the designing and production. Until the drilling guide, crown and abutment are finished, patient could receive the surgery for placing the implants and crown in the final appointment. Therefore, one appointment can be eliminated.

Table 41, impact of Resequence the task: D: IOS and CT-scan

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Resequence the task: Discuss treatment plan	Time	+	The task of making IOS and CT scan is resequenced from after medical checkings to before, the waiting time of 15 days is eliminated.
	Cost	0	Only the order of task is changed, thus there is no cost addition or reduction.
	Quality	0	Only the order of task is changed, thus there is no changes on quality.
	Flexibility	0	Only the order of task is changed, thus there is no changes on flexibility.

Therefore the overall impact of TO-BE TO-BE 1 can be described as below.

Table 42, overall impact on time, cost and quality of all the modifications for TO-BE TO-BE 2 (crown)

Number	*Name of the modification*	*Time*	*Cost*	*Quality*	*Flexibility*
1	*Elimination of the task: check-up*	*0*	+	*0*	*0*
2	*Elimination of the task: D/H:hygiene*	*0*	+	*0*	-
3	*Elimination of the task: Expose implant*	+	+	*0*	*0*
4	*Elimination of the task: make individual impression trays*	+ +	+ +	*0*	*0*
5	*Elimination of the task: make impressions*	*0*	+ +	*0*	*0*
6	*Addition of task: make drilling guide*	-	- -	+	+
7	*Integral technology: IOS and CT-scan*	-	- -	+	+
8	*Task automation: Process IOS and CT scan*	*0*	-	+ +	+ +
9	*Resequencing the task: IOS and CT-scan*	+	*0*	*0*	*0*
10	*Resequencing the task: place implant*	*0*	*0*	*0*	*0*
	Overall impact caused by the modifications	*2 plus positive*	*2 plus positive*	*4 plus Strong positive*	*3 plus positive*

Shown as the table above, the TO-BE TO-BE 2 model has the similar performance with TO-BE TO-BE 1, only on the time dimensions it has a better result. A evaluation for all the TO-BE TO-BE models of crown treatment are presented as figure below.

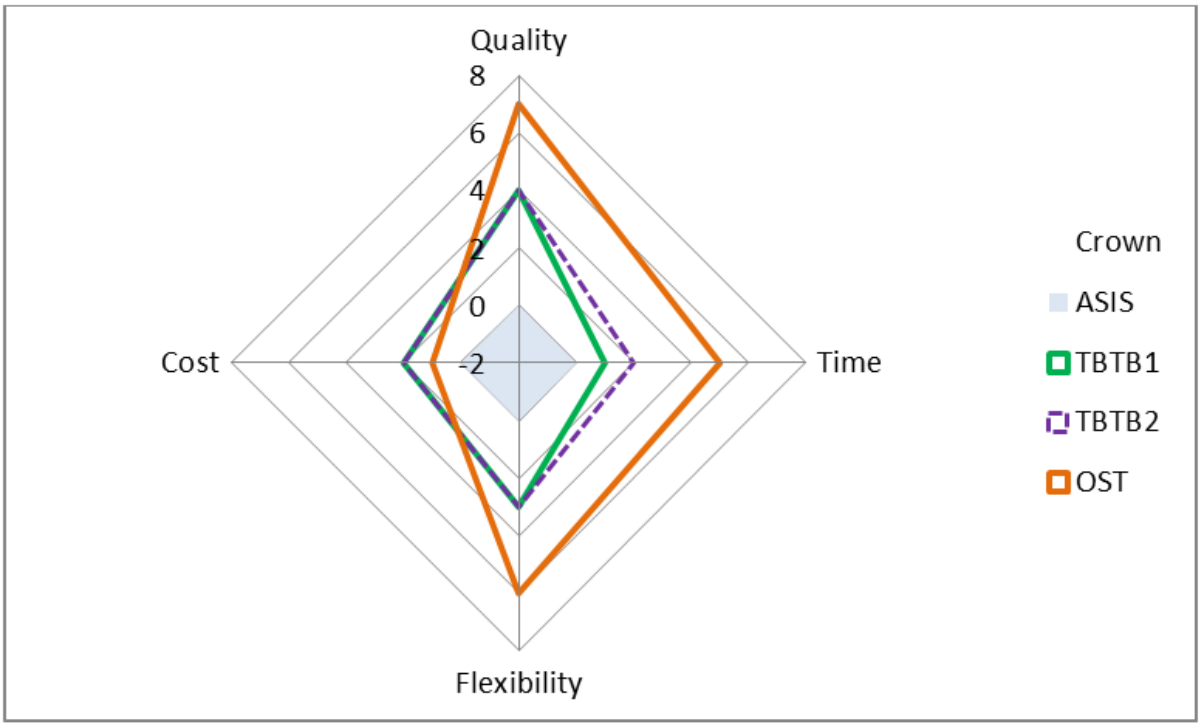


Figure 55, Evaluation of TO-BE TO-BE models for crown treatment

Apparently, the OST has stronger positive impact on dimensions of time, quality and flexibility than all the others, however, on the dimension of cost, its positive impact is also the smallest. In terms of TO-BE TO-BE 1 and TO-BE TO-BE 2, their improvement are more even spread. With the general evaluation, several interviews with dental professionals are set up. During the interviews, we receive great interests on OST and majority of dental professionals believe that it has the most potential to have further improvement with the fast development of digital technology. For some dentist, the task sequence of TO-BE TO-BE 2 is not recommended since it will raise more risk for the success of the treatment. And for the TO-BE TO-BE 1, they believe that it will be realizable in the near future not

far future, since most of the technologies there are already being developed for a long time. With the overwhelming votes for OST, it is selected as the most promising redesign.

B.2 modifications for each TO-BE TO-BE models (prosthesis treatment)

For prosthesis treatment, the TO-BE 2 model is selected as the benchmark, since all the models are developed originally from it. The overview of all the modifications for each TO-BE TO-BE models of prosthesis treatment are presented as below.

Table 43, overview of all the modifications for each TO-BE TO-BE models (prosthesis treatment)

Redesign heuristics	*TO-BE 2 vs DMS*	*TO-BE 1 vs TO-BE TO-BE 1*	*TO-BE 2 vs TO-BE TO-BE 2*
Resequence the task:	D: Discuss treatment plan		D: make IOS and CT-scan
			D: place 3 mini-implants
			D: make 3D picture
Task elimination:	D: individual impressions	D: individual impressions	D: individual impressions
	L: prepare registration bite	L: prepare registration bite	L: prepare registration bite
	D: register bite	D: register bite	D: register bite
Addition of task:	D: hygiene	D: make 3D picture	D: make 3D picture
	D: make X-ray and 3D photo		
Integral technology	D: Make IOS and CT-scan	D: Make IOS and CT-scan	D: Make IOS and CT-scan
Task automation	D: process IOS, 3D picture and CT-scan	D: process IOS, 3D picture and CT-scan	D: process IOS, 3D picture and CT-scan

The modifications for DMS are already explained and evaluated in chapter 4, here we are only going to explain and evaluate the modifications that are not mentioned in chapter 4. After that, the overall impact of other TO-BE TO-BE models will be given.

For the TO-BE TO-BE 1 model, all the modification are mentioned in DMS except the single task of making 3D picture since we only discussed the combined task of making X-ray and 3D picture. Here a description and evaluation of this task will be given.

Addition of task: make 3D picture

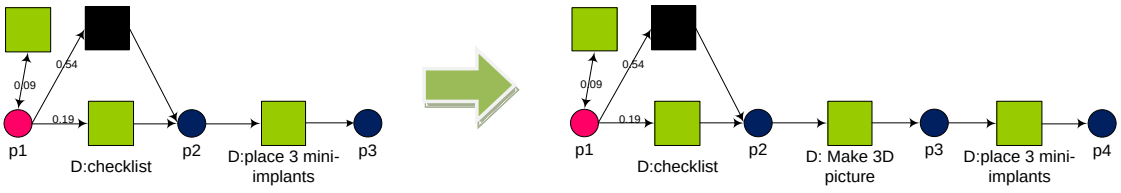


Figure 56, Addition of task: make 3D picture

The 3D picture is taken because the patient is edentulous. For edentulous patient, their bone will resorb or atrophy when there is no tooth root to stimulate the bone. Bone resorbtion can lead to serious changes in facial appearance, thus 3D picture is taken for watching the facial appearance. In later steps, the 3D picture could also be used for designing the prosthesis in simulation software.

Table 44, impact of Addition of task: make IOS and 3D picture

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Addition of task: make X-Ray and 3D picture	Time	0	The waiting time of this task is same with placing 3 mini-implants (see appendix for details) and the waiting time of 3 mini-implants is eliminated. Therefore, in total there is no changes on the waiting time. The average execution time is 12.5 minutes.
	Cost	- -	Cost addition on resource of dentist and instrument tool for medical imagining of X-ray.
	Quality	+	Addition of partial digitalized task.
	Flexibility	+	Making 3D photo can be done by dentist and any others.

Therefore the overall impact of TO-BE TO-BE 1 can be described as below.

Table 45, overall impact on time, cost and quality of all the modifications for TO-BE TO-BE 1 (prosthesis)

Number	*Name of the modification*	*Time*	*Cost*	*Quality*	*Flexibility*
1	*Addition of task: make 3D photo*	*0*	- -	+	+
2	*Integral technology: Make IOS and CT scan* *Task elimination: individual impressions, prepare registration bite, register bite*	+ +	+	+	+
3	*Task automation: Process IOS, 3D picture and CT scan*	*0*	-	+ +	+ +
	Overall impact caused by the modifications	*2 plus positive*	*2 minus Negative*	*4 plus Strong positive*	*4 plus Strong positive*

Shown as the table above, TO-BE TO-BE 1 model have strong positive impact on the dimensions of quality and flexibility. There is an improvement on time as well, however, on the dimension of cost, it has a negative impact.

When it comes to TO-BE TO-BE 2, the modifications that we do not mentioned are the resequence of task making IOS and CT-scan, placing 3 mini-implants and making 3D picture.

Resequence the task: D: IOS and CT-scan; placing 3 mini-implants and making 3D picture

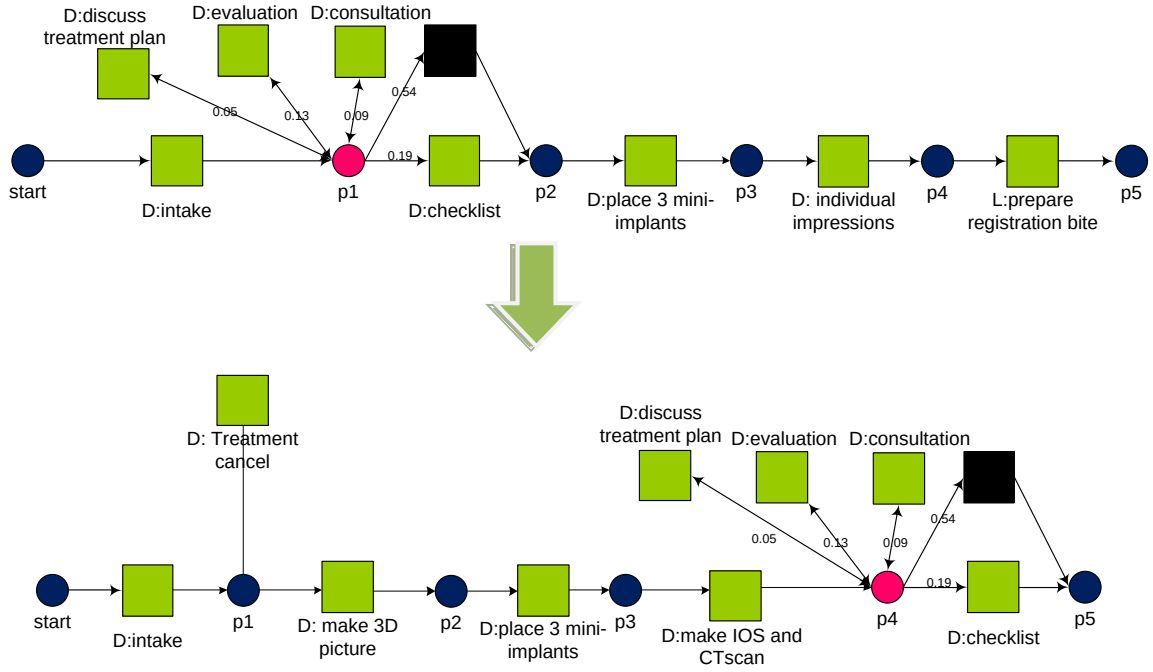


Figure 57, Resequence the task: D: IOS and CT-scan; D: placing 3 mini-implants; D: make 3D picture

The reason to resequence these three tasks is to eliminate one appointment of them. In TO-BE TO-BE 1, after the intake and medical checking, there will be an appointment for these tasks. In TO-BE TO-BE 2, immediately after the intake, patient will receive the 3D picture taking, surgery for placing 3 mini-implants and IOS and CT-scan. After that, a certain number of medical checking will be given to examine the availability of patient for treatment in second appointment. If all the checks are positive, then the 3D picture, IOS and CT-scan will be processed and send to the dental lab for the designing and production of the prosthesis. However, if the checks are not all positive, the treatment plan can still change based on the 3 mini-implants. For example, the removable prosthesis is an option which can be connected to the mini-implants and for a certain time it will be removed and cleaned, and actually it is an very popular solution at this moment. An evaluation based on the resequence of these three tasks are given as below.

Table 46, impact of Resequence the task: D: IOS and CT-scan

Name of the modification	*Dimensions*	*Impact on the process*	*Descriptions*
Resequence the task: Discuss treatment plan	Time	+	The waiting time of these tasks is the same with the waiting time for placing 3 mini-implants and it is around 11 days. Thus, 11 days is eliminated here.
	Cost	0	Only the order of task is changed, thus there is no cost addition or reduction.
	Quality	0	Only the order of task is changed, thus there is no changes on quality.
	Flexibility	0	Only the order of task is changed, thus there is no changes on flexibility.

Therefore the overall impact of TO-BE TO-BE 2 can be described as below.

Table 47, overall impact on time, cost and quality of all the modifications for TO-BE TO-BE 2 (prosthesis)

Number	*Name of the modification*	*Time*	*Cost*	*Quality*	*Flexibility*
1	*Addition of task: make 3D photo*	*0*	- -	+	+
2	*Integral technology: Make IOS and CT scan* *Task elimination: individual impressions, prepare registration bite, register bite*	+ +	+	+	+
3	*Task automation: Process IOS, 3D picture and CT scan*	*0*	-	+ +	+ +
4	*Resequence the task:* *D: make IOS and CT-scan;* *D: place 3 mini-implants;* *D: make 3D picture*	+	*0*	*0*	*0*
	Overall impact caused by the modifications	*3 plus positive*	*2 minus Negative*	*4 plus Strong positive*	*4 plus Strong positive*

Shown as the table above, TO-BE TO-BE 1 model have strong positive impact on the dimensions of quality and flexibility. There is an improvement on time as well, however, on the dimension of cost, it has a negative impact. A evaluation for all the TO-BE TO-BE models of prosthesis treatment are presented as figure below.

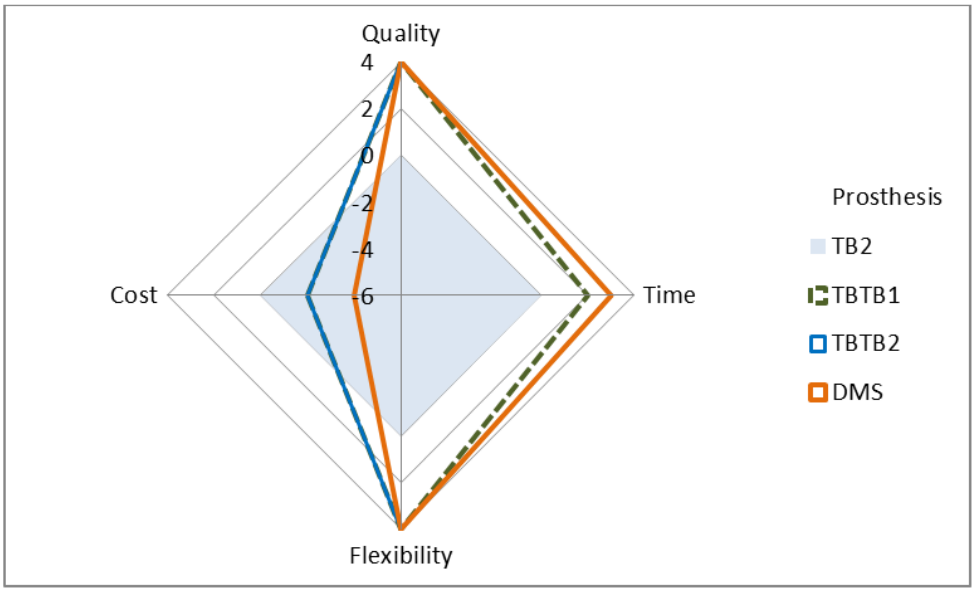


Figure 58, Evaluation of TO-BE TO-BE models for prosthesis treatment

In the comparison between TO-BE TO-BE 1 and TO-BE TO-BE 2, the latter one has better performance on the dimension of time and same performance on other three dimensions. In the comparison between TO-BE TO-BE 2 and DMS, the former has better performance on dimension of cost and same performance on the other three dimensions. Thus, on aspect of performance, TO-BE TO-BE 2 are the best redesign. However, all the redesigns have negative impact on the dimension of cost. During the interview, similarly dentist are skeptical about the task sequence of TO-BE TO-BE 2 will raise more risk for the success of the treatment. And in the comparison between TO-BE TO-BE 1 and DMS, dental professionals pay more attention on improvement on the dimension of time instead of cost in this situation, since they believe that the cost of new technologies will be decreased sharply in the far future and an redesign of dental vale chain with less throughput time is more valuable at this moment. Therefore, DMS is selected as the most promising redesign in this study.

B.3 TO-BE TO-BE 1 of crown treatment

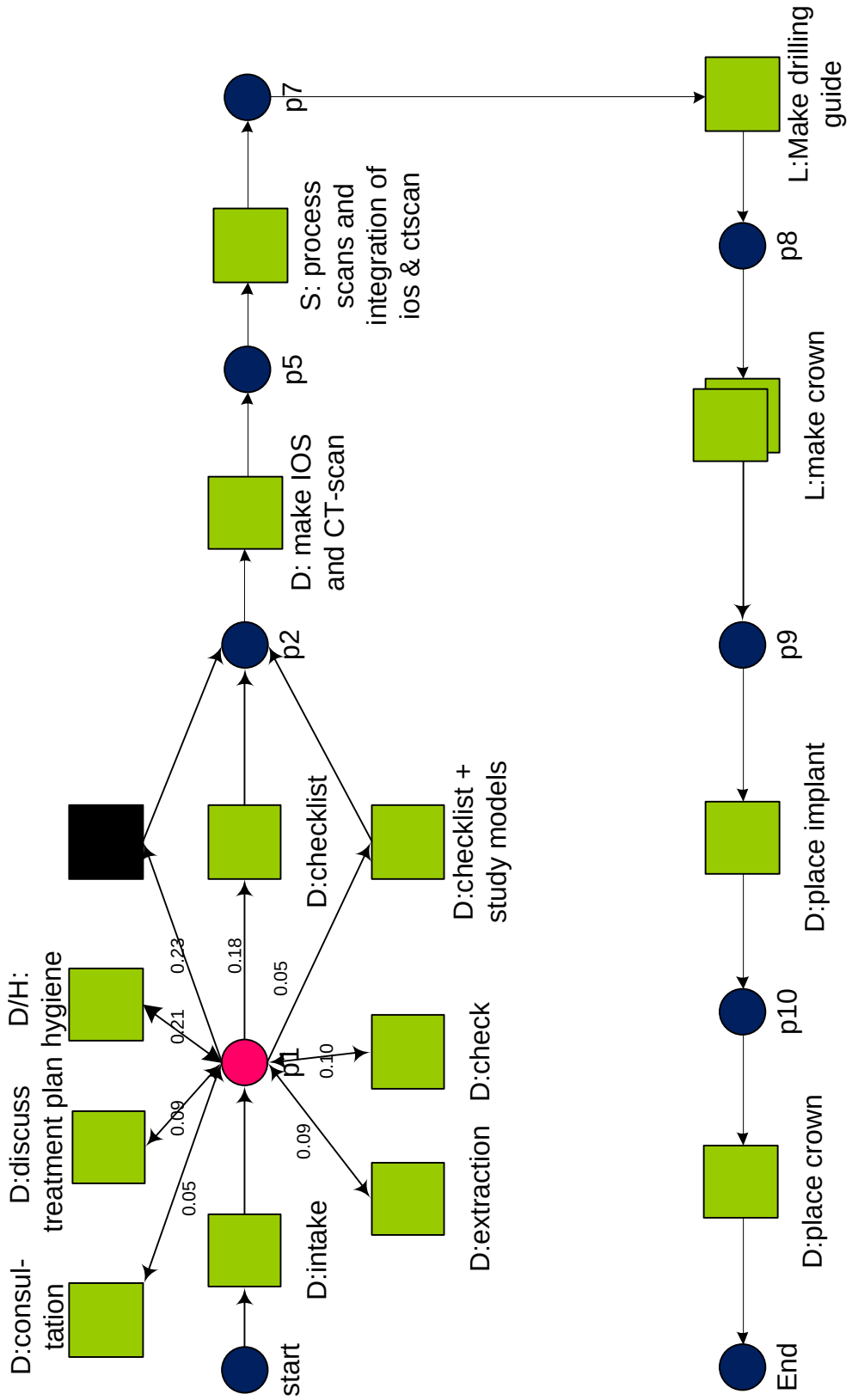


Figure 59, TO-BE TO-BE 1 of crown treatment

B.4 TO-BE TO-BE 2 of crown treatment

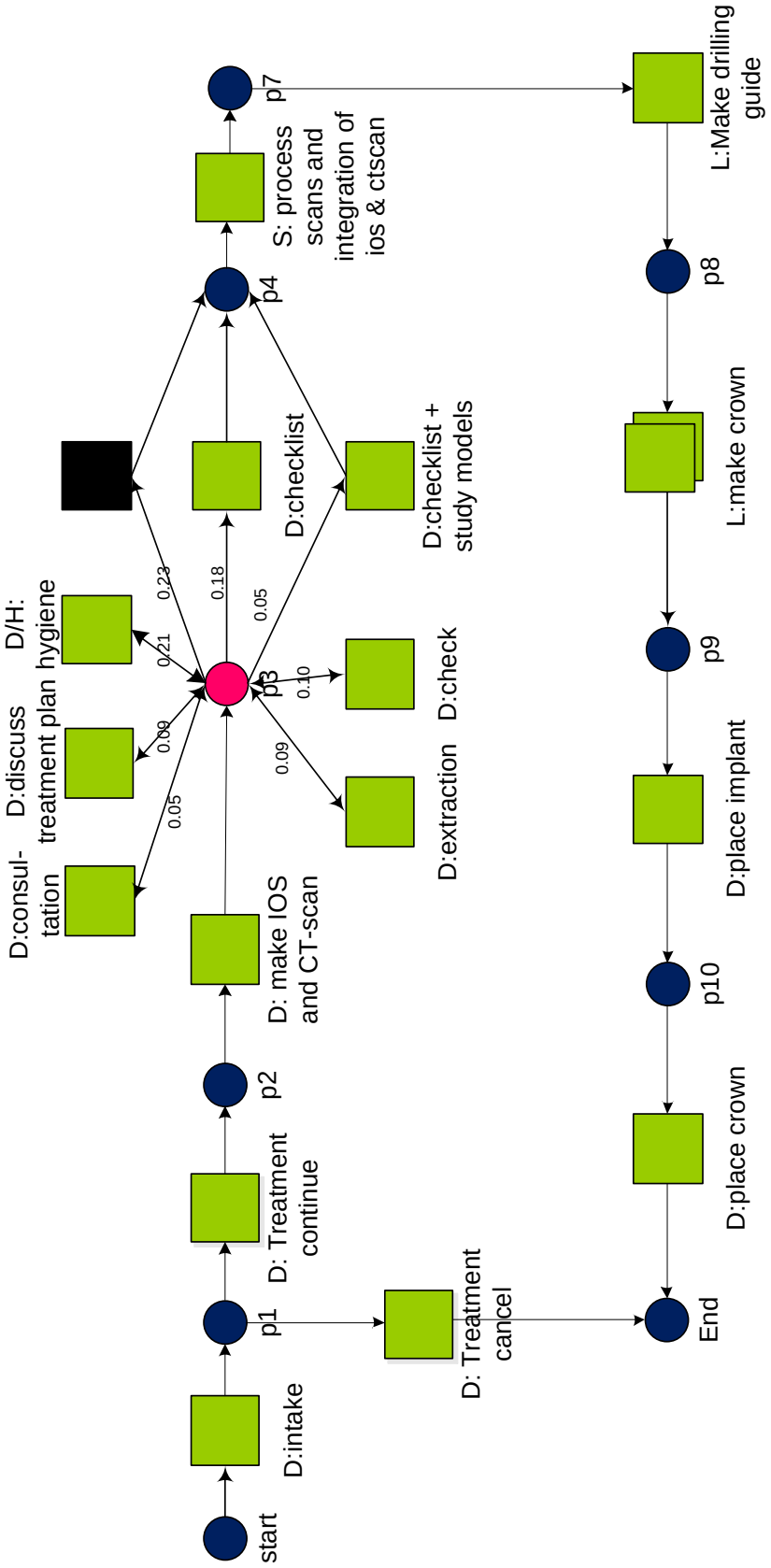


Figure 60, TO-BE TO-BE 2 of crown treatment

B.5 TO-BE TO-BE 1 of prosthesis treatment

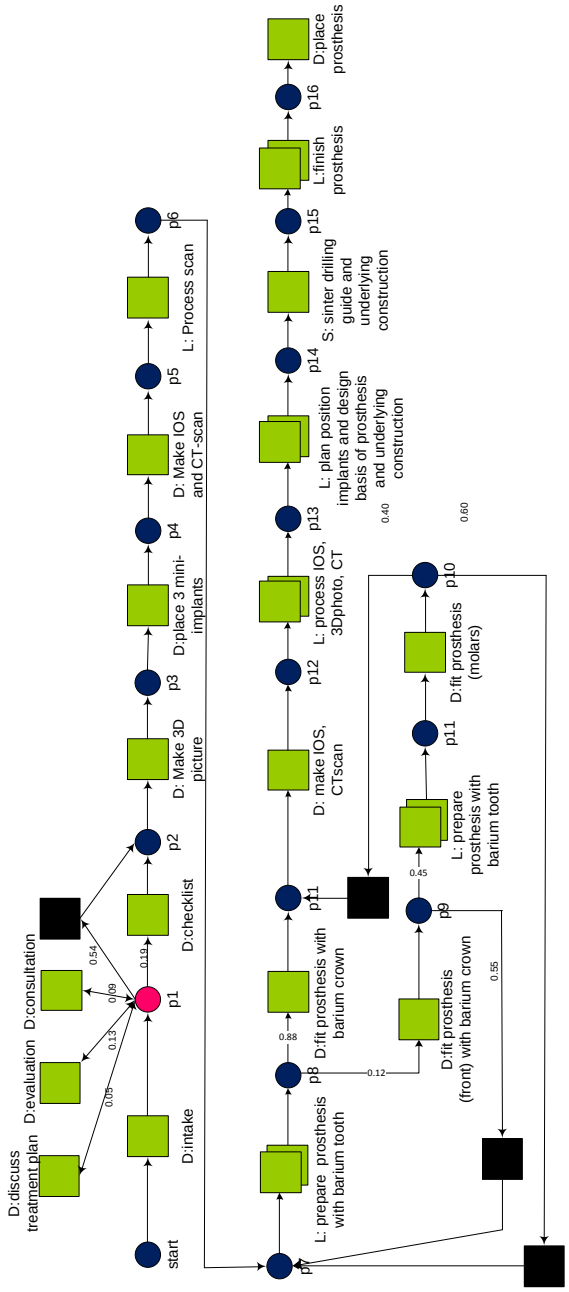


Figure 61, TO-BE TO-BE 1 of prosthesis treatment

B.6 TO-BE TO-BE 2 of prosthesis treatment

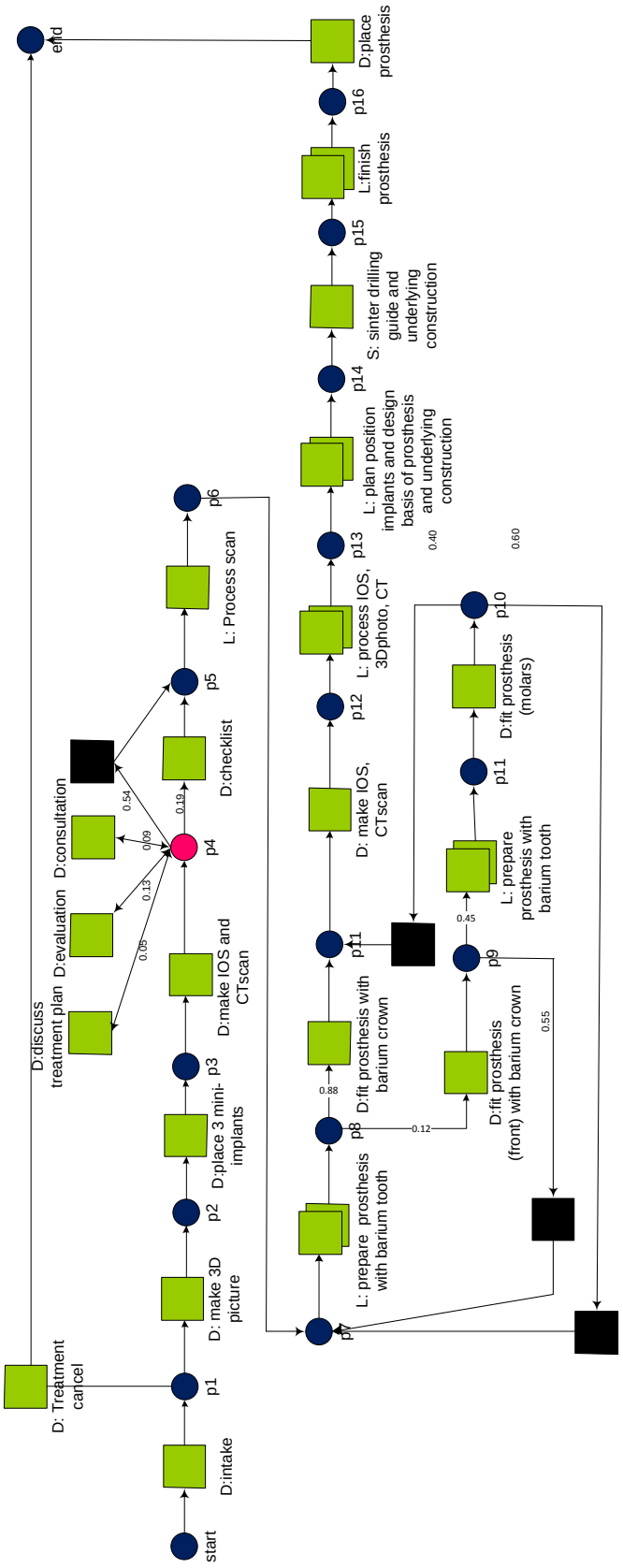


Figure 62, TO-BE TO-BE 2 of prosthesis treatment

C Simulation Model

The appendix describes in more detail the simulation models programmed in CPNtools. Section B.1 presents the assumptions or setup of the simulation. Section B.2 explains the overview structure of the model in CPNtools. Section B.3 explains how the theoretical analysis is addressed.

C.1 Assumptions

In order to give an fair comparison, all the assumptions or defined parameters in the ITI project have been used in this project. The structure of the declarations of the simulation is showed as below.

Figure 63, structure of declarations

Declarations	*Description*
standard declarations	In the standard declarations (showed in the figure above), all the data type, such as integer and string are defined.
Control flow declarations	The identity number of the patient is declared in the control flow declarations.

Groups and Resources declarations	In the group and resources declarations, the list of dentist, hygienist and all the dental employees are defined here.
	Several examples are selected and explained as below.
	Table 48, list of dentist
	`colset DENTISTS = subset STRING with ["Bruyn", "Andriessen", "M_van_Mook", "Groningen", "Blom", "Liu", "Pull_ter_Gunne", "Bekker", "Tahmaseb", "Kruger", "Sips", "Huigen", "Rijkens", "Prof__Dr__D__Wismeyer", "Fokas", "Brouwer", "Korac___Umanjec", "Elsas", "Zygogiannis", "Vriens", "Wismeijer"];`
	In the ITI project, all the dentists are derived by using the process mining of dental event log. Thus, all the names are from real case. In total, there are 21 dentists in the simulation.
	Table 49, list of hygienist
	`colset MH = subset STRING with ["M__Schot_Wolters", "M_van_Mook", "Thijm_Westerveld","Horst", "Coenraadts"];`
	In terms of the task of hygiene, not only the dentist could be the resource, but also hygienist could. In total, there are 5 hygienist in the simulation.
	Table 50, list of experienced dentist
	`colset EXPERIENCED_DENTIST = subset STRING with ["Blom",`

	"Korac___Umanjec", "Zygogiannis", "Huigen", "M_van_Mook", "Tahmaseb", "Prof__Dr__D__Wismeyer", "Wismeijer"]; Based on the result of process mining in the event log, some of the dentists are performed better than others. In the ITI project, they are regarded as the experienced dentists. In total, there are 8 experienced dentists in the simulation. **Table 51, list of inexperienced dentist** colset INEXPERIENCED_DENTIST = subset STRING with ["Bruyn", "Andriessen", "Sips", "Rijkens", "Fokas", "Groningen", "Brouwer", "Liu", "Elsas", "Vriens", "Pull_ter_Gunne", "Bekker", "Kruger"]; As mentioned in table 13 and 15, there are total 21 dentists in the simulation and 8 of them are experienced. Thus, the rest of the 13 dentists are regarded as inexperienced dentist.
Start case declarations	For each patient, the arriving time is defined in the "start case declarations"
Other declarations	In other declarations, the data type of number of implants and the probability for executing task are declared here. In addition, the type of token in the place are defined as well
Lab declarations	All the resources in the dental lab are defined in this sector
Product Color Sets for places	Some extra product color sets are defined here
Execution time functions	The execution time for each tasks are defined here
waiting time functions	All the waiting time functions for every tasks are defined here
Log declarations	In order to track some transitions, the execution log is also used in the simulation. All the log function are declared in this sector
Distribution functions	In this simulation, the arrival rate of patient and majority of the waiting time are assumed following the log-logistic distribution. However, in the CPNtools, there is system function for the log-logistic distribution directly. Therefore, the function of log-logistic distribution are defined
Other functions	In the other functions, the clock model is defined and realized here as mentioned in the section 5.1 Basic setup. All the time transformation among days, hours and minutes are implemented here. Especially, the arrival size of patients are defined as well.
file functions	For further development, some file functions are defined for importing data from files here
Guard functions	In Guard functions, the probability for each optional tasks are defined
Global reference	All the global reference value are defined

C.2 Creation of the simulation model of OST

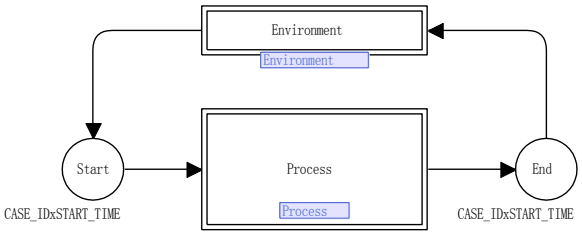


Figure 64, the overview of OST in CPN tool

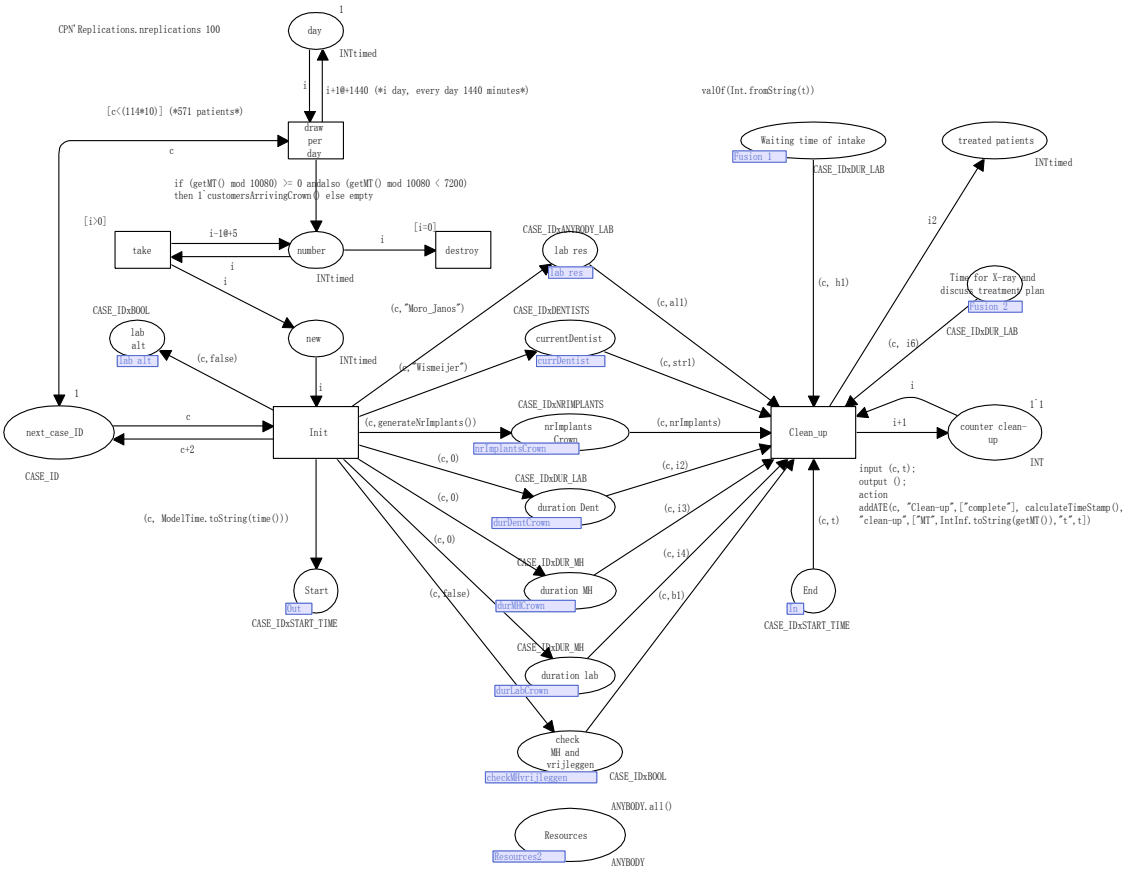


Figure 65, Environment of the OST in CPN tool

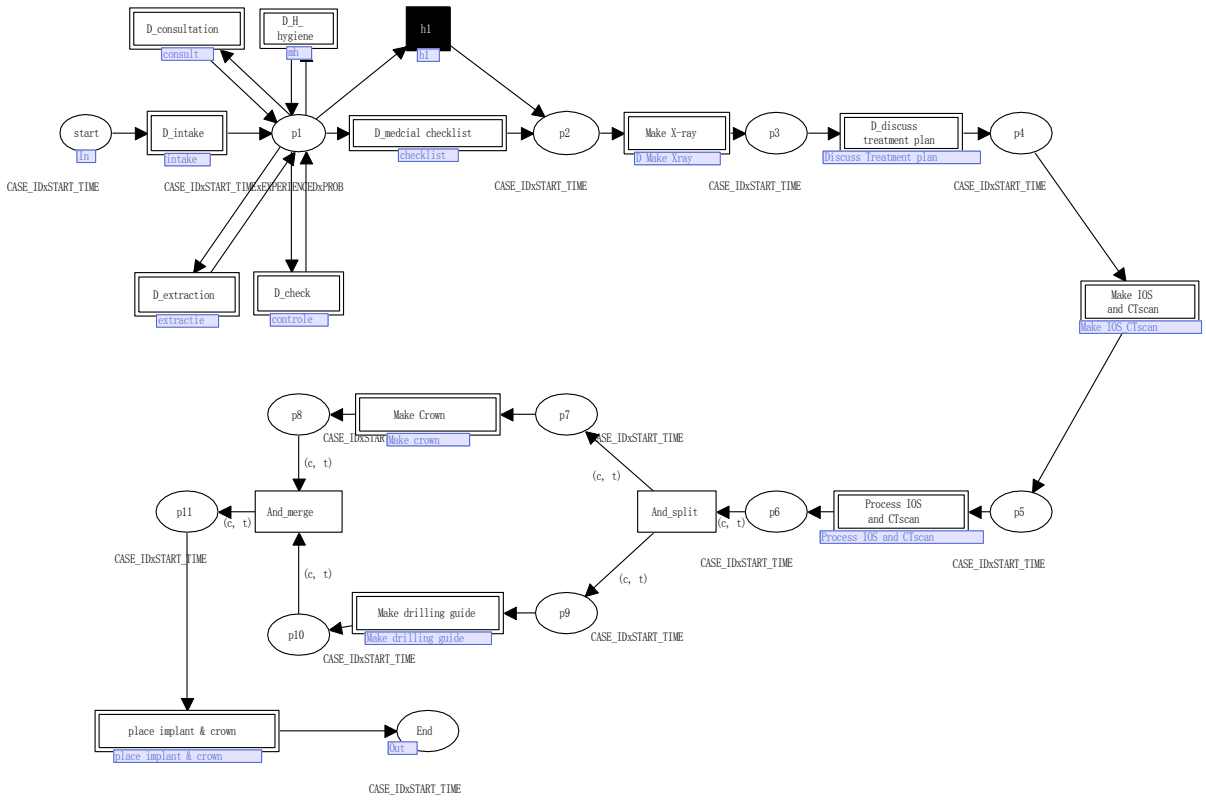


Figure 66, the process of OST in CPN tool

C.3 Creation of the simulation model of DMS

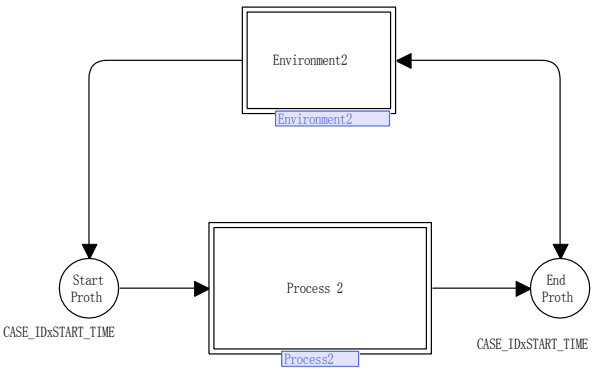


Figure 67, the overview of DMS in CPN tool

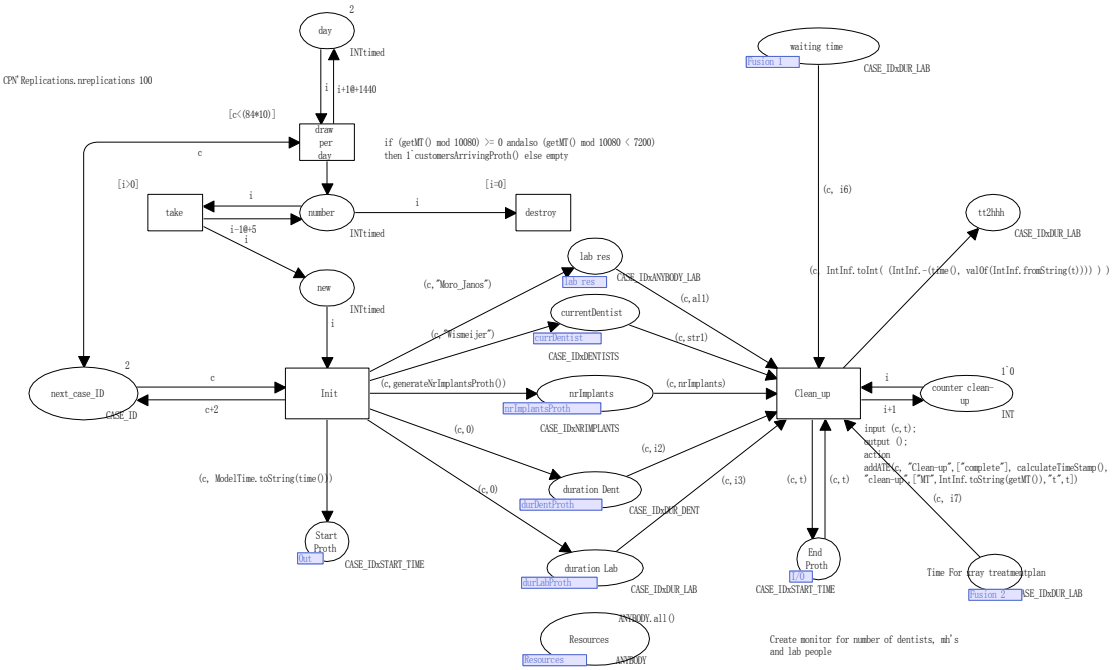


Figure 68, the environment of DMS in CPN tool

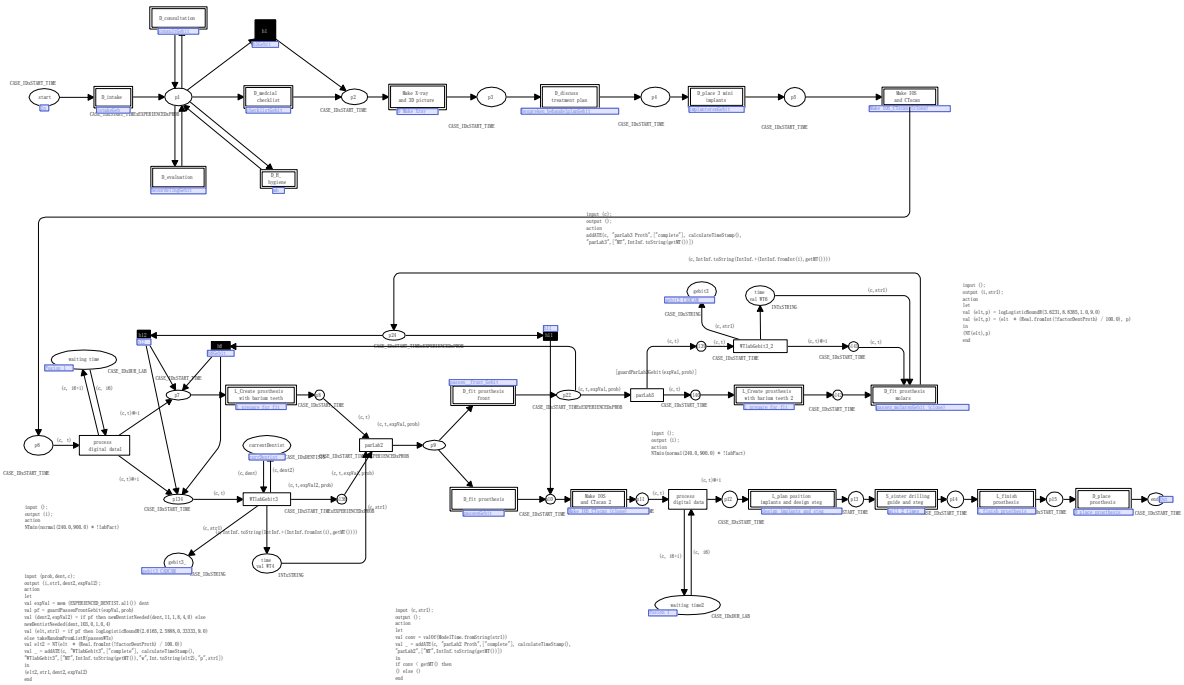


Figure 69, the process of DMS in CPN tool

C.4 Waiting time and execution time for new tasks

C.4.1 One stop treatment

All the timing information of new task is based on existing data from ITI project or has been estimated by dental professionals. In terms of the waiting time, all the treatment tasks will be finished adjacently by the same dentist within one appointment day, thus there is no waiting time for any tasks. For each task, the description of the execution time are presented as below.

- *D: make X-ray*: No existing data was available for this task. The execution time is determined based on the interviews with dental professionals in ACTA.
- *D: make IOS and CT-scan*: tasks for making IOS and CT-scan are all already used in different prosthesis treatment, thus the execution time is based on the existing data of IOS that has been used in the TO-BE 1 model and CT-scan that has been used in the TO-BE 2 model.
- *D: process IOS and CT-scan*: the execution time is based on existing data that involves processing the IOS and CT-scan that have been made for 19 cases.
- *D: design drilling guide*: the drilling guide is actually already been used in the prosthesis treatment, therefore the execution time for designing drilling guide in TO-BE 2 model has been taken.
- *D: 3D printing the drilling guide*: although in the prosthesis treatment, there is a task for making the drilling guide however it is totally different case. In our model, 3D printer is used and the drilling guide could be automatically printed after the designing. Therefore, no execution data was available for this task. The execution time is determined based on the interviews with dental professionals in ACTA.
- *D: 3D printing and crown & abutment*: the same reason as above, no execution data was available for this task. The execution time is determined based on the interviews with dental professionals in ACTA.

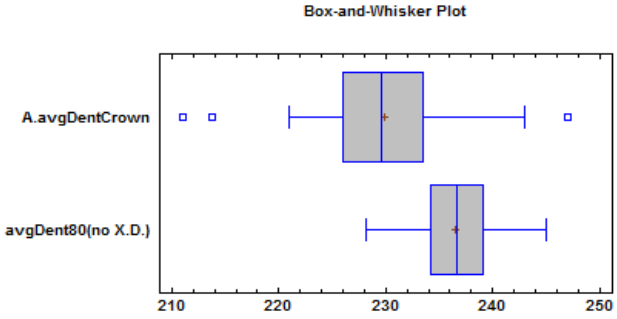
C.4.2 Digital mini-implants solution

Similarly, all the timing information of new task is based on existing data from ITI project or has been estimated by dental professionals. For each task, the description of the waiting time and execution time are presented as below.

- *D: make X-ray and 3D photo*: the waiting time is assumed as similar for the placing of 3 mini-implants in TO-BE 2 model, since making X-ray, 3D photo and placing 3 mini-implants should be finished within one appointment in DMS and the waiting time for placing 3mini-implants is switched to front. The execution time of X-ray is already obtained from OST. In terms of making 3D photo, no existing data was available for this task. Due to the function of making 3D photo is also to collect the medical image of patient, and an discussion with Ali Tahmaseb, we assume that the execution time of making 3D photo is following the same distribution with X-ray.
- *L: process IOS, 3D photo and CT-scan*: the waiting time and execution time of this task are considered the same with the task “process scan” in TO-BE 1 model, since the time of task “process scan” is the duration elapses from the end of the intra-oral scanning till the time the processed scan arrives in the dental lab. Both this task and “process scan” are regarded as out-sourcing tasks and take similar duration of time.
- *D: Hygiene*: the task of hygiene is already used in crown treatment, thus the waiting time and execution time are from OST

C.5 The result of T-TEST

T-TEST on the dentist's working time between OST and previous models



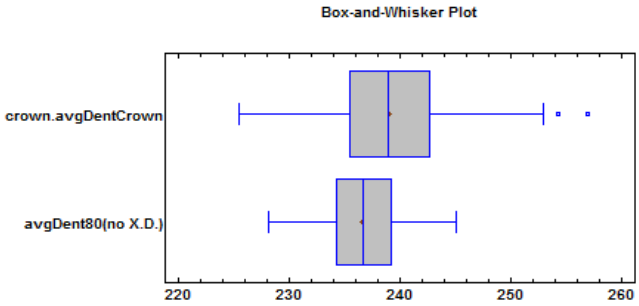
95% confidence intervals
Diff. of means: -6.63144 +/- -1.32484 [-5.3066, -7.95628]
Ratio of variances: [1.84078, 4.06607]

Comparison of Means
Null hypothesis: difference = 0
t statistic = -9.88403 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 2.73582 Two-sided P-value = . 0

Diagnostics
Shapiro-Wilks P-values = .6617 and .7717

Figure 70, dentist's working time comparison between AS-IS model and OST with 80% time reduction on 3D printing



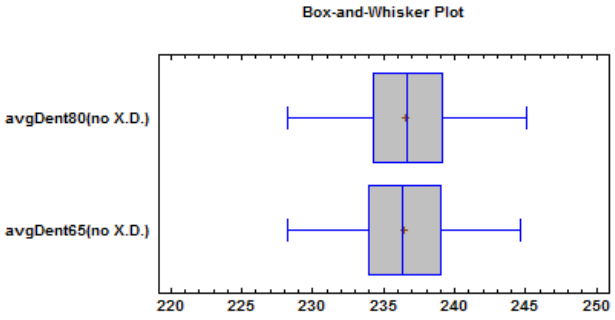
95% confidence intervals
Diff. of means: 2.54165 +/- -1.39865 [3.9403, 1.143]
Ratio of variances: [2.12681, 4.69788]

Comparison of Means
Null hypothesis: difference = 0
t statistic = 3.58955 Two-sided P-value = . 4

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 3.16093 Two-sided P-value = . 0

Diagnostics
Shapiro-Wilks P-values = .5819 and .7717
Lag 1 autocorrelation = . 123 +/- .1960, --.1009 +/- .1960

Figure 71, dentist's working time comparison between AS-IS model and OST with 80% time reduction on 3D printing



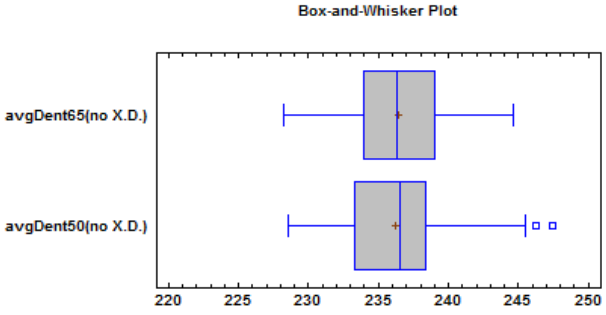
95% confidence intervals
Diff. of means: .133885 +/- .979039 [-.845154, 1.11292]
Ratio of variances: [.643513, 1.42145]

Comparison of Means
Null hypothesis: difference = 0
t statistic = .269677 Two-sided P-value = .7877

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = .956411 Two-sided P-value = .8250

Diagnostics
Shapiro-Wilks P-values = .7717 and .3326

Figure 72, dentist's working time comparison between OST with 80% and 65% time reduction on 3D printing.



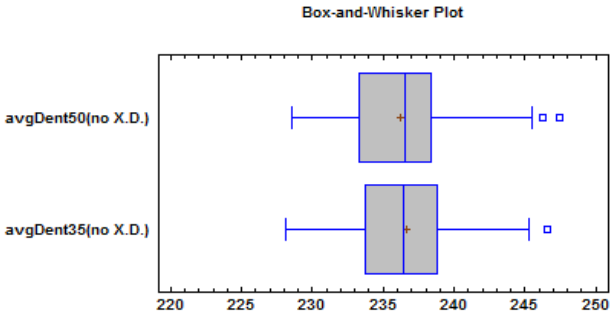
95% confidence intervals
Diff. of means: .260019 +/- 1.01923 [-.759212, 1.27925]
Ratio of variances: [.60057, 1.32659]

Comparison of Means
Null hypothesis: difference = 0
t statistic = .503088 Two-sided P-value = .6155

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = .892587 Two-sided P-value = .5729

Diagnostics
Shapiro-Wilks P-values = .3326 and .1422
Lag 1 autocorrelation = - .-765 +/- .1960, . 777 +/- .1960

Figure 73, dentist's working time comparison between OST with 65% and 50% time reduction on 3D printing.



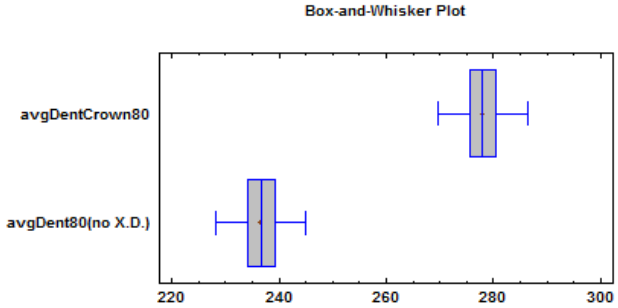
95% confidence intervals
Diff. of means: -.465253 +/- 1.05833 [-1.52359, .59308]
Ratio of variances: [.646597, 1.42826]

Comparison of Means
Null hypothesis: difference = 0
t statistic = -.866919 Two-sided P-value = .3870

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = .960994 Two-sided P-value = .8435

Diagnostics
Shapiro-Wilks P-values = .1422 and .4495
Lag 1 autocorrelation = . 777 +/- .1960, . 440 +/- .1960

Figure 74, dentist's working time comparison between OST with 50% and 35% time reduction on 3D printing.



95% confidence intervals
Diff. of means: 41.4021 +/- .968071 [40.434, 42.3702]
Ratio of variances: [.672842, 1.48623]

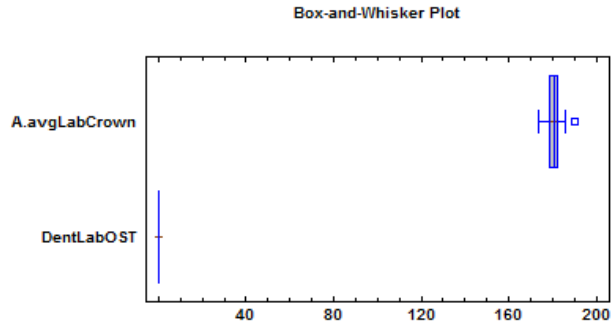
Comparison of Means
Null hypothesis: difference = 0
t statistic = 84.3387 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 1 Two-sided P-value = 1.0000

Diagnostics
Shapiro-Wilks P-values = .7717 and .7717

Figure 75, dentist's working time comparison between duration with and without X-ray and discuss treatment plan

T-TEST on the dental lab working time between OST and previous models



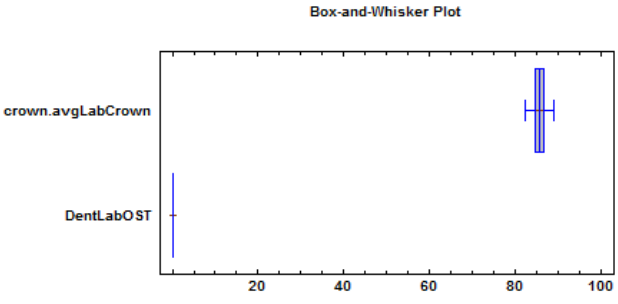
95% confidence intervals
Diff. of means: 180.695 +/- .554331 [181.25, 180.141]
Ratio of variances: [1.#INF, 1.#INF]

Comparison of Means
Null hypothesis: difference = 0
t statistic = 646.796 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 1.#INF Two-sided P-value = . 0

Diagnostics
Shapiro-Wilks P-values = .9535 and . -1
Lag 1 autocorrelation = . 801 +/- .1960, . 0 +/- .1960

Figure 76, dental lab time comparison between AS-IS model and OST with 80% time reduction on 3D printing



95% confidence intervals
Diff. of means: 85.6199 +/- .292453 [85.9124, 85.3275]
Ratio of variances: [1.#INF, 1.#INF]

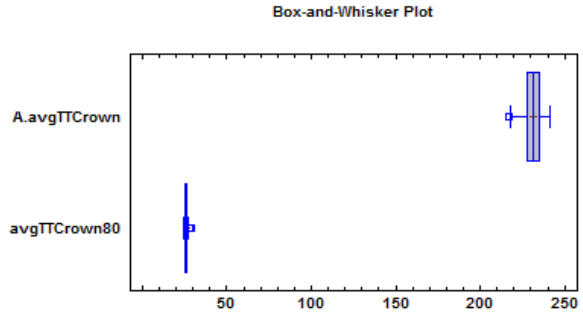
Comparison of Means
Null hypothesis: difference = 0
t statistic = 580.909 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 1.#INF Two-sided P-value = . 0

Diagnostics
Shapiro-Wilks P-values = .3787 and . -1
Lag 1 autocorrelation = . 77 +/- .1960, . 0 +/- .1960

Figure 77, dental lab time comparison between TO-BE model and OST with 80% time reduction on 3D printing

T-TEST on the total throughput time between OST and previous models



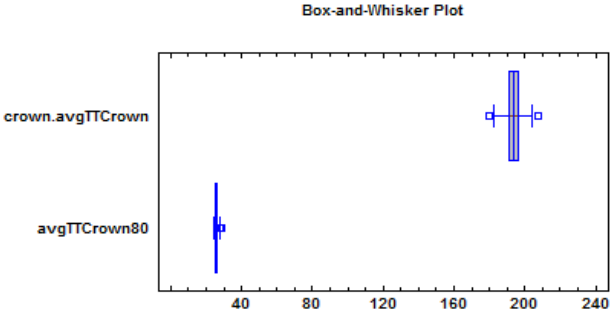
95% confidence intervals
Diff. of means: 205.11 +/- -1.07899 [206.189, 204.031]
Ratio of variances: [35.7399, 78.9456]

Comparison of Means
Null hypothesis: difference = 0
t statistic = 377.022 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 53.1179 Two-sided P-value = . 0

Diagnostics
Shapiro-Wilks P-values = .1307 and .5309
Lag 1 autocorrelation = .1072 +/- .1960, --.1299 +/- .1960

Figure 78, throughput time comparison between AS-IS model and OST with 80% time reduction on 3D printing



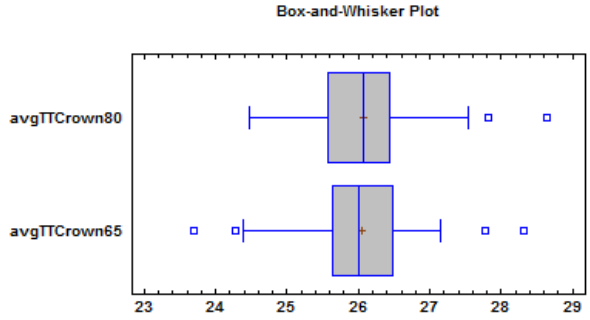
95% confidence intervals
Diff. of means: 167.261 +/- -.992137 [168.253, 166.269]
Ratio of variances: [30.119, 66.5295]

Comparison of Means
Null hypothesis: difference = 0
t statistic = 334.336 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 44.7639 Two-sided P-value = . 0

Diagnostics
Shapiro-Wilks P-values = .9553 and .5309

Figure 79, throughput time comparison between TO-BE model and OST with 80% time reduction on 3D printing



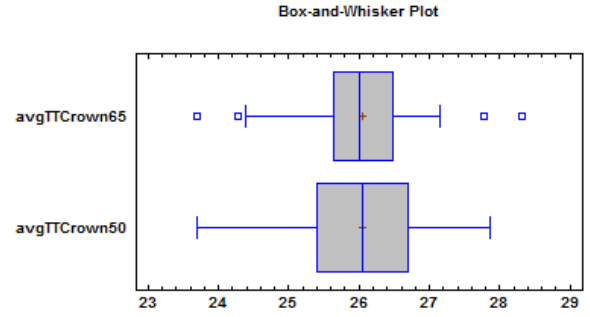
95% confidence intervals
Diff. of means: .0293928 +/- .206993 [-.1776, .236386]
Ratio of variances: [.663159, 1.46485]

Comparison of Means
Null hypothesis: difference = 0
t statistic = .280025 Two-sided P-value = .7798

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = .985609 Two-sided P-value = .9427

Diagnostics
Shapiro-Wilks P-values = .5309 and .6479

Figure 80, throughput time comparison between OST with 80% and 65% time reduction on 3D printing



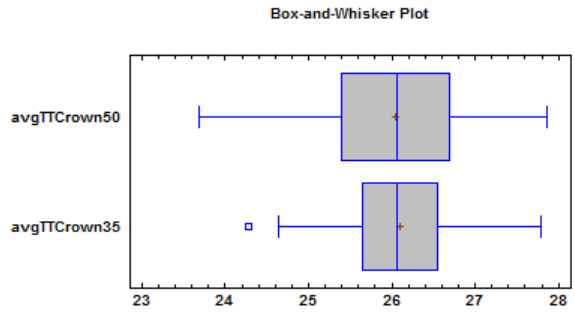
95% confidence intervals
Diff. of means: -.00191486 +/- .225821 [-.227736, .223907]
Ratio of variances: [.493554, 1.09021]

Comparison of Means
Null hypothesis: difference = 0
t statistic = -.0167219 Two-sided P-value = .9867

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = .733536 Two-sided P-value = .1249

Diagnostics
Shapiro-Wilks P-values = .6479 and .3776
Lag 1 autocorrelation = --.1079 +/- .1960, . 585 +/- .1960

Figure 81, throughput time comparison between OST with 65% and 50% time reduction on 3D printing



95% confidence intervals
Diff. of means: -.0479019 +/- -.218464 [.170562, -.266366]
Ratio of variances: [1.08291, 2.39203]

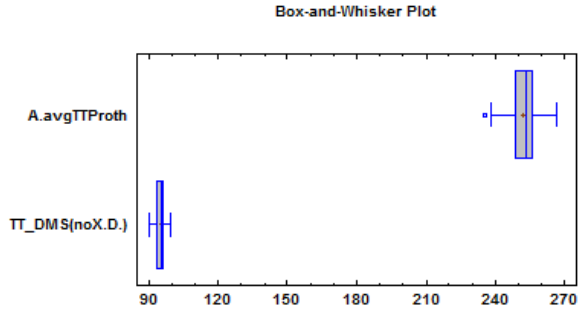
Comparison of Means
Null hypothesis: difference = 0
t statistic = -.432545 Two-sided P-value = .6658

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 1.60946 Two-sided P-value = . 187

Diagnostics
Shapiro-Wilks P-values = .3776 and .9030
Lag 1 autocorrelation = . 585 +/- .1960, - .-411 +/- .1960

Figure 82, throughput time comparison between OST with 50% and 35% time reduction on 3D printing

T-TEST on the total throughput time between DMS and previous models



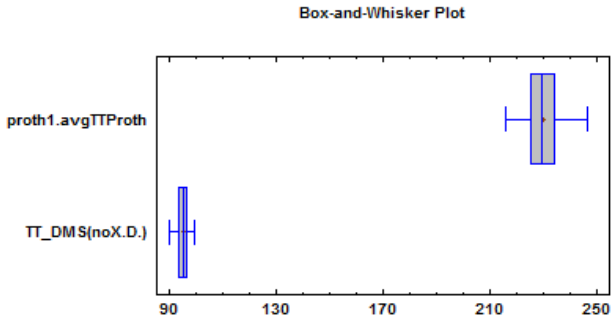
95% confidence intervals
Diff. of means: 157.092 +/- -1.29538 [158.387, 155.796]
Ratio of variances: [7.00586, 15.4752]

Comparison of Means
Null hypothesis: difference = 0
t statistic = 240.154 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 10.4124 Two-sided P-value = . 0

Diagnostics
Shapiro-Wilks P-values = .2316 and .5271
Lag 1 autocorrelation = --.1462 +/- .1960, . 246 +/- .1960

Figure 83, throughput time comparison between AS-IS and DMS model



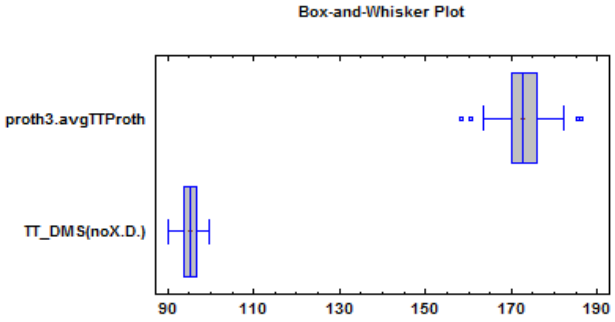
95% confidence intervals
Diff. of means: 134.38 +/- -1.37288 [135.753, 133.008]
Ratio of variances: [7.94874, 17.5579]

Comparison of Means
Null hypothesis: difference = 0
t statistic = 193.875 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 11.8137 Two-sided P-value = . 0

Diagnostics
Shapiro-Wilks P-values = . 888 and .5271
Lag 1 autocorrelation = . 227 +/- .1960, . 246 +/- .1960

Figure 84, throughput time comparison between TO-BE 1 and DMS model



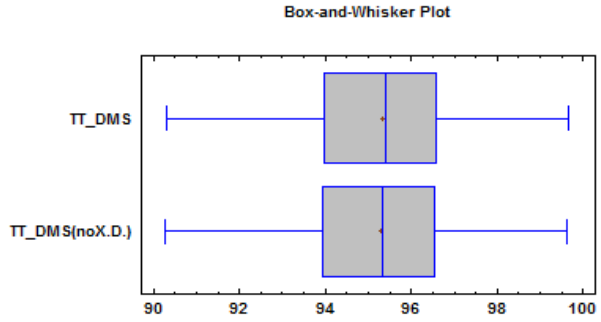
95% confidence intervals
Diff. of means: 77.4711 +/- -1.06366 [78.5347, 76.4074]
Ratio of variances: [4.51284, 9.96838]

Comparison of Means
Null hypothesis: difference = 0
t statistic = 144.117 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 6.70714 Two-sided P-value = . 0

Diagnostics
Shapiro-Wilks P-values = .9349 and .5271
Lag 1 autocorrelation = . 396 +/- .1960, . 246 +/- .1960

Figure 85, throughput time comparison between TO-BE 2 and DMS model



95% confidence intervals
Diff. of means: .0394808 +/- .540012 [-.500531, .579493]
Ratio of variances: [.672842, 1.48623]

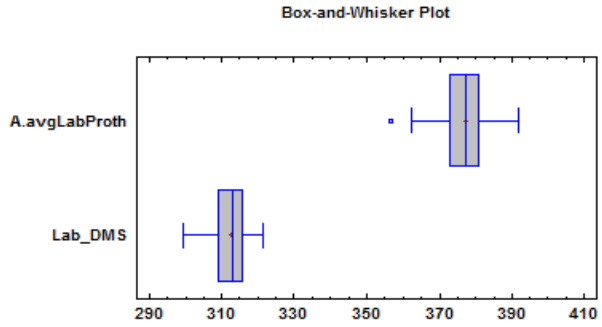
Comparison of Means
Null hypothesis: difference = 0
t statistic = .144176 Two-sided P-value = .8855

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 1 Two-sided P-value = 1.0000

Diagnostics
Shapiro-Wilks P-values = .5271 and .5271
Lag 1 autocorrelation = . 246 +/- .1960, . 246 +/- .1960

Figure 86, throughput time comparison between duration with or without X-ray and discuss treatment plan

T-TEST on the dental lab working time between DMS and previous models



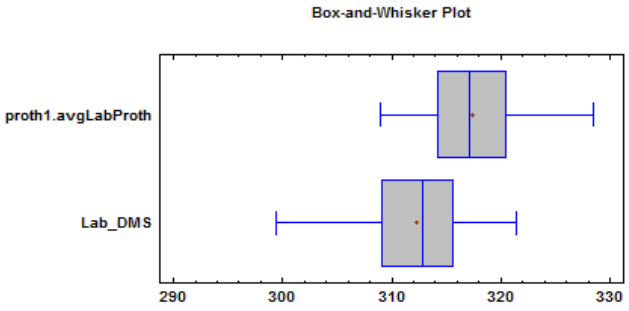
95% confidence intervals
Diff. of means: 64.8 +/- 1.51312 [66.3131, 63.2869]
Ratio of variances: [1.34713, 2.97567]

Comparison of Means
Null hypothesis: difference = 0
t statistic = 84.5108 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 2.00216 Two-sided P-value = . 6

Diagnostics
Shapiro-Wilks P-values = .7103 and .1203
Lag 1 autocorrelation = . 866 +/- .1960, . 534 +/- .1960

Figure 87, dental lab time comparison between AS-IS and DMS model



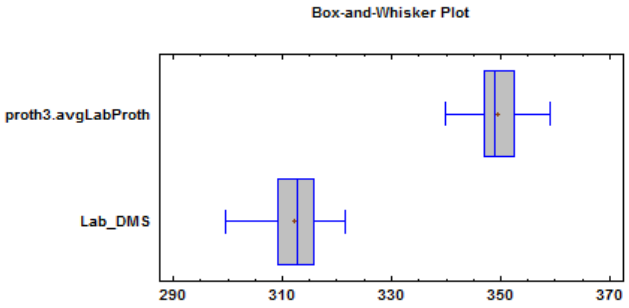
95% confidence intervals
Diff. of means: 5.09278 +/- 1.26 [3.83278, 6.35278]
Ratio of variances: [.729775, 1.61199]

Comparison of Means
Null hypothesis: difference = 0
t statistic = 7.97069 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 1.08462 Two-sided P-value = .6869

Diagnostics
Shapiro-Wilks P-values = .1239 and .1203
Lag 1 autocorrelation = --.1378 +/- .1960, . 534 +/- .1960

Figure 88, dental lab time comparison between TO-BE 1 and DMS model



95% confidence intervals
Diff. of means: 37.1287 +/- 1.21797 [35.9108, 38.3467]
Ratio of variances: [.637765, 1.40875]

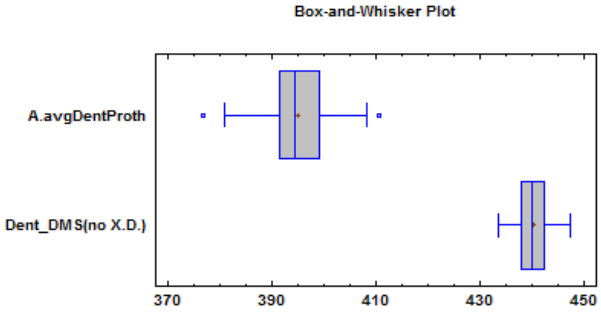
Comparison of Means
Null hypothesis: difference = 0
t statistic = 60.1152 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = .947869 Two-sided P-value = .7905

Diagnostics
Shapiro-Wilks P-values = .2128 and .1203
Lag 1 autocorrelation = .2118 +/- .1960, . 534 +/- .1960

Figure 89, dental lab time comparison between TO-BE 2 and DMS model

T-TEST on the dentist's working time between DMS and previous models



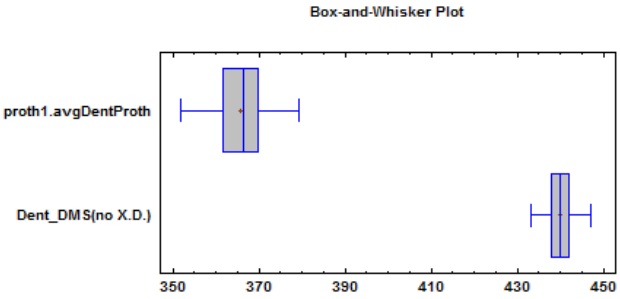
95% confidence intervals
Diff. of means: -45.0554 +/- -1.37156 [-43.6839, -46.427]
Ratio of variances: [3.01172, 6.65257]

Comparison of Means
Null hypothesis: difference = 0
t statistic = -64.9415 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 4.47612 Two-sided P-value = . 0

Diagnostics
Shapiro-Wilks P-values = .9417 and .1536
Lag 1 autocorrelation = - .-636 +/- .1960, . 422 +/- .1960

Figure 90, dentist's working time comparison between AS-IS and DMS model



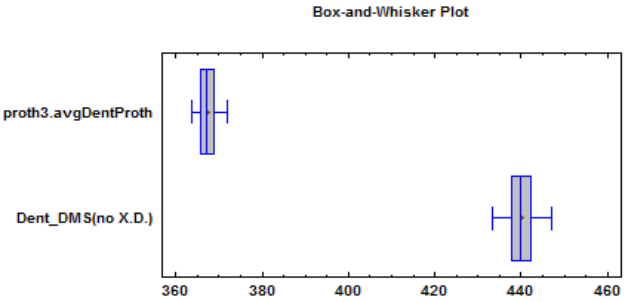
95% confidence intervals
Diff. of means: -74.2264 +/- -1.23601 [-72.9904, -75.4624]
Ratio of variances: [2.32311, 5.1315]

Comparison of Means
Null hypothesis: difference = 0
t statistic = -118.648 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 3.45269 Two-sided P-value = . 0

Diagnostics
Shapiro-Wilks P-values = .5292 and .1536
Lag 1 autocorrelation = - . -8 +/- .1960, . 422 +/- .1960

Figure 91, dentist's working time comparison between TO-BE 1 and DMS model



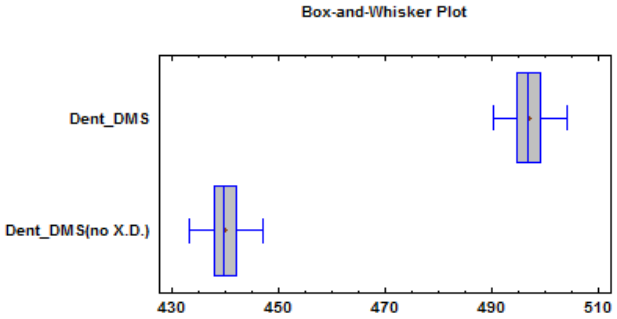
95% confidence intervals
Diff. of means: -72.6702 +/- -.702378 [-71.9678, -73.3725]
Ratio of variances: [.296438, .6548]

Comparison of Means
Null hypothesis: difference = 0
t statistic = -204.221 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = .440577 Two-sided P-value = . 1

Diagnostics
Shapiro-Wilks P-values = . 138 and .1536
Lag 1 autocorrelation = . 92 +/- .1960, . 422 +/- .1960

Figure 92, dentist's working time comparison between TO-BE 2 and DMS model



95% confidence intervals
Diff. of means: 56.8523 +/- .826827 [56.0255, 57.6791]
Ratio of variances: [.672842, 1.48623]

Comparison of Means
Null hypothesis: difference = 0
t statistic = 135.595 Two-sided P-value = . 0

Comparison of Sigmas
Null hypothesis: ratio = 1
F statistic = 1 Two-sided P-value = 1.0000

Diagnostics
Shapiro-Wilks P-values = .1536 and .1536
Lag 1 autocorrelation = . 422 +/- .1960, . 422 +/- .1960

Figure 93, dentist's working time comparison between duration with and without X-ray and discuss treatment plan